USGS-NPS Vegetation Mapping Program

VEGETATION OF SHENANDOAH NATIONAL PARK IN RELATION TO ENVIRONMENTAL GRADIENTS

Final Report (v1.1)

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LIST OF ABBREVIATIONS AND ACRONYMS

AA = Accuracy Assessment
ASCII = American Standard Code for Information Interchange
AVIRIS = Advanced Visible and Infra-Red Imaging Sensor
CART = Classification and Regression Tree
CLDA = Canonical Linear Discriminant Analysis
CTI = Compound Topographic Index
DEM = Digital Elevation Model
DOQQ = Digital Ortho-Photograph Quarter Quadrangle
ELU = Ecological Land Unit
GCP = Ground Control Point
GIS = Geographic Information System
GPS = Global Positioning System
LSC = Leetown Science Center
Landsat TM = Landsat Thematic Mapper
NAD = North American Datum
NASA = National Aeronautic and Space Administration
NMDS = Non-Metric Multidimensional Scaling
NPS = National Park Service
RMI = Relative Moisture Index
RMSE = Root Mean Square Error
SAF = Society of American Foresters
SHEN = Shenandoah National Park
TCI = Topographic Convergence Index
TRMI = Topographic Relative Moisture Index
USGS = United States Geological Survey
USNVC = United States National Vegetation Classification System
UTM = Universal Transverse Mercator
VAGAP = Virginia Gap Analysis Project
VANHP = Virginia Natural Heritage Program
WGS = World Geodetic System

EXECUTIVE SUMMARY

This report documents the results of a four year research project to assess and map vegetation communities of Shenandoah National Park. The project was a collaborative effort between Shenandoah National Park, the US Geological Survey-Leetown Science Center, the Virginia Department of Conservation and Recreation-Division of Natural Heritage, the University of Maryland Center for Environmental Science-Appalachian Laboratory, and NatureServe. While set up as a research project rather than strictly a mapping effort, the result of the project is a new map of vegetation distribution in Shenandoah National Park based on U.S. National Vegetation Classification System standards. Additional products include a classification scheme of vegetation communities in the Park based on field sampling of 311 vegetation plots, maps of landforms, ecological land units, and environmental gradients, and an assessment of the relationship between vegetation community distribution and environmental gradients. Additionally we tested the capability of mapping vegetation communities using hyperspectral remote sensing, environmental gradient maps, and statistical modeling.

We classified 34 vegetation communities at the association level of the National Vegetation Classification System within Shenandoah National Park. Three community types were newly classified and described. We mapped vegetation communities to the association level using AVIRIS spring 2000 and summer 2001 imagery, and we filled in missing areas with Landsat TM imagery. We validated the results using internal cross validation and through an accuracy assessment conducted at 224 field plots in the summer of 2004, and at 68 field plots in 2005. Results of accuracy assessment range from 88% overall accuracy from internal validation to 67% overall accuracy from field validation. As a whole, statistical analysis indicated that bedrock parent material, soil fertility, elevation, and topographic position are the most important, interrelated environmental factors influencing major vegetation patterns in Shenandoah National Park. In addition, vegetation communities occurred across a number of environmental types as categorized into ecological land unit types.

The results of this project demonstrate innovative application of the latest techniques in vegetation mapping using hyperspectral imaging and landscape modeling. Mapping results are generally consistent with previous mapping efforts (by area) and show that the USNVC can be reliably mapped with techniques other than manual interpretation of aerial photography. In fact, by exploiting the fine spectral specificity of hyperspectral imaging and the spatial heterogeneity of environmental gradient models, much more information can potentially be extracted on growing environments than can be visually interpreted. The fact that association-level classes can be mapped using these techniques is an important finding.

1. INTRODUCTION

Accurate and up-to-date vegetation maps are fundamental to management of national parks. Activities as diverse as park planning, fire management, wildlife research, and visitor interpretation all require current maps of vegetation distribution. In recognition of this need, the US Geological Survey (USGS) and the National Park Service (NPS) jointly initiated a program for mapping vegetation in National Parks to the United States National Vegetation Classification system (USNVC) standard. Procedures and protocols were developed for field sampling, photo interpretation, and accuracy assessment and a funding program was established to initiate mapping at NPS units. As of 2006, 109 of 270 NPS units nationwide have vegetation mapping projects underway (Brown 2006). However, since the program's inception in 1994, only 39 parks have completed vegetation mapping projects (Brown 2006). Clearly these projects require a substantial investment of time and resources for field sampling, vegetation classification, and image interpretation. Thus, research that can that improve the efficiency, reliability, and information content extracted from vegetation mapping protocols is needed.

Planning began in 1999 for a research project funded by the USGS Natural Resources Preservation Program (NRPP) to assess vegetation community distribution in relation to environmental gradients in Shenandoah National Park (SHEN). While not officially a part of the USGS-NPS vegetation mapping program, this project was conducted to provide SHEN with updated maps of vegetation distribution using the USNVC standard, and at the same time to investigate new methods of mapping vegetation communities and their growing environments within the park.

This project was initiated in 2000 as a partnership between Shenandoah National Park, the USGS-Leetown Science Center (USGS-LSC), Virginia Department of Conservation and Recreation – Division of Natural Heritage (VANHP), and NatureServe. In 2002, researchers at the University of Maryland, Center for Environmental Science-Appalachian Laboratory (now of the University of Wisconsin, Madison) were brought into the project to provide hyperspectral remote sensing expertise. Field sampling was conducted in 2001, 2002, and 2003. Image analysis and environmental gradient modeling were conducted in 2001-2004, and draft vegetation association maps were completed in 2004. An initial accuracy assessment was conducted in 2004, and an additional accuracy assessment was completed in 2005. Revised map products were produced in 2005.

Environmental gradient modeling, sampling design, and remote sensing activities were led by the USGS-LSC (Young); field sampling, vegetation community data analysis, community classification, and accuracy assessment field work were led by the VANHP (Fleming, Walton, and Patterson); crosswalk of the vegetation classification into USNVC classes was led by NatureServe (Sneddon);

hyperspectral image analysis and vegetation community mapping were led by Univ. of Wisconsin-Madison (Townsend and Foster).

1. 1. Background

One of the goals of the U.S. Geological Survey-Leetown Science Center (USGS-LSC) is to provide clients within the U.S. Department of the Interior with biological research results that will assist in managing the Nation's public lands. A critical information need within many national parks is accurate and up-to-date information on vegetation composition, distribution, and change. Shenandoah National Park (SHEN) in particular has pressing management issues that rely on an accurate vegetation map including visitor safety, fire management, forest insect pest management, and threatened and endangered species preservation. The park's landscape is the result of prior land use history and 70 years of protection as a national park. Historically, park management has promoted forest protection with an emphasis on fire suppression and minimal vegetation manipulation. However, SHEN forests have undergone dramatic changes in forest composition in the last decade as a result of gypsy moth defoliation, hemlock woolly adelgid infestation, southern pine beetle infestation, ice storms, large fires, and floods.

Shortly after the park's establishment in 1935, vegetation communities were mapped by Berg and Moore (1941). The park was mapped on a topographic base in 19 sections at a scale of 1 inch to 1 mile (1:63,360). Twelve forest cover types were mapped using a Society of American Foresters (SAF) classification scheme. In addition to canopy cover type, age classes and acreage burned were also recorded for cover types. No accuracy assessment was conducted for the mapping effort and only forest cover types were mapped (no ground or shrub cover estimates were provided). However, accuracy of this mapping effort is considered good (Teetor 1988) and this map should serve as an excellent reference for examining successional changes and disturbance patterns that have occurred in the park over the past 70 years.

Subsequent to the Berg and Moore (1941) map, the park's vegetation map of record was a map developed from 1985-1988 (Teetor 1988) using low altitude aerial photography imaged as 35 mm color infrared slides by the Virginina Department of Game and Inland Fisheries (circa 1983-1984). The classification was focused on forest canopy species and was based on Society of American Foresters (SAF) cover classes. This effort provided an adequate map for characterizing broad forest cover types and has been used extensively for resource management, monitoring, and research projects. An extensive accuracy assessment was conducted with over 2000 ground plots, and overall accuracy of the mapping effort was reported to be 70% (Teetor, 1987). However, this map was based solely on dominant overstory vegetation, and the park is divided into only 7 forest cover types. Forest cover class boundaries were interpreted by tracing over aerial slide images projected on a wall. This mapping method undoubtedly introduced positional errors into the final map as systematic errors inherent in aerial photography were not controlled. In addition, conversion of this map between new implementations of GIS software packages over the years resulted in introduced errors including shifts in vegetation types and open, unclassified polygons along stand boundaries. Park resource inventories and monitoring efforts now depend heavily on the use of digital maps for planning and assessing ecological condition. Discrepancies in the accuracy of this vegetation map and the massive changes that have occurred in the forests of the park during the last 25 years justified the need for a new assessment of vegetation composition and distribution.

In addition to the Teetor (1988) map, several other efforts have attempted to map vegetation in SHEN. Cibula (1981) used Landsat Multi-Spectral Scanner (MSS) imagery to map forest types. However, Teetor (1988) reported the map to be unreliable, perhaps due to the coarse resolution of the early Landsat sensors (80 meter pixel size). The Southern Appalachian Man and the Biosphere (SAMAB) program developed a regional land cover map through a private contractor (Pacific Meridian) using Landsat TM imagery (circa 1990-1994). This map was based on SAF cover types, and omitted understory vegetation and ecological parameters. Accuracy of this map is unknown. Due to these limitations, researchers and managers never adopted the SAMAB map. The Virginia Gap Analysis Project (VAGAP) derived vegetation types for the entire Commonwealth of Virginia from Landsat TM imagery (c. 1993). This effort attempted to go beyond dominant overstory vegetation to community types based on the newly implemented United States National Vegetation Classification System (USNVC). Despite the improvement in the classification system, VAGAP could still not provide the range of vegetation types, accuracy, and scale of treatment needed by researchers and managers.

The USNVC is a hierarchical classification system, defining communities by physiognomic structure at broad levels and then floristically at finer levels (Grossman et al. 1998, Anderson et al. 1998, NatureServe 2002). Unlike the Society of American Foresters cover classes that focus only on dominant tree cover, the USNVC defines plant communities at the lowest level of the hierarchy (the association level) on the basis of characteristic herbaceous and shrub species, in addition to forest canopy species. The USNVC system also has the potential to define characteristic mixed forest associations that may better reflect natural conditions rather than attempting to lump forest types under a single dominant tree species type as does the SAF system. The USNVC was recently adopted as a Federal standard guiding vegetation mapping at U.S. government agencies, state agencies, and non-governmental organizations.

Vegetation mapping in the deciduous forests of the eastern U.S. can be a difficult task. Classification of spectral patterns from aerial or satellite imagery into species or community-based categories can be challenging due to the nature of the mixed forest communities. Since aerial and satellite imagery provide an image from the top of the canopy downward, it is often difficult if not impossible to directly image ground cover and shrub species. This difficulty often necessitates mapping only to broadly defined groups when using remotely sensed imagery alone, and past efforts (as evidenced above) have been somewhat unsatisfactory from an ecological perspective. However, vegetation does respond predictably to ecological gradients in the steep terrain of the park. Integrated ecological modeling and predictive mapping approaches have shown promise for mapping plant communities by exploiting the predictable relationship between vegetation distribution and environmental gradients (Bridge and Johnson 2000, Franklin 1995, Swanson et al. 1988). For example, eastern hemlock (*Tsuga canadensis*) is known to track closely with gradients in soil moisture and available light, occurring in regular pattern on moist, cool, north-facing slopes and in moist, shaded ravines. Conversely, pitch pine (*Pinus rigida*) commonly occurs on drier, well-drained soils with a more southerly exposure. While this is not an entirely deterministic relationship (past land disturbances, successional and gap dynamics, soil characteristics, and micro-climates also strongly influence vegetation occurrence), knowledge of the tendency of vegetation to occur in definable ecological associations may allow a predictive approach to mapping.

Researchers in the United States and elsewhere have had success using a predictive approach to mapping forest composition by modeling ecological associations between vegetation and environmental gradients (extensively reviewed in Franklin 1995). Several authors have created models of environmental gradients by deriving measures of soil moisture availability, available light, and topographic shape from digital geospatial data (Gallant and Wilson 1996, Iverson et al. 1997, Dubayah and Rich 1995). By assessing components of landform using digital elevation models, it is possible to model the spatial distribution of climatic and topographic variables that have strong relationships to vegetation occurrence. These data are especially useful for spatial extrapolation of vegetation distribution between observations collected at field plots (Hong et al. 1998). Combining field collected vegetation plot data, satellite image derived measures of plant characteristics (e.g. tasseled cap and other vegetation indices), and statistical classification, regression, and ordination techniques has resulted in useful predictive models of vegetation distribution (Franklin et al. 2000, Davis and Goetz 1990). However, predictive models that are based solely on direct gradients are useful only for prediction of potential natural vegetation patterns. Since current vegetation pattern is highly correlated to past disturbance (Glenn et al., 1999), information on disturbance regimes (derived from satellite or aerial imagery or historic land use maps) should be incorporated in predictive models to get an accurate idea of current vegetation distribution.

Data-rich hyperspectral imagery represents one of the latest advances in sensor technology applicable to landscape mapping of vegetation (Treitz and Howarth 1999). Measurement of electromagnetic radiation from hundreds of spectral bands introduces hundreds of new predictor variables that may aid in discrimination of vegetation communities. Several studies have documented attempts to harness the potential discriminating power of hyperspectral data for vegetation mapping in recent years (Martin, Newman et al. 1998; Treitz and Howarth 1999; Cochrane 2000; Gong, Pu et al. 2001; Foster and Townsend 2004; Thenkabail, Enclona et al. 2004). These studies are at the forefront of a broad and diverse effort to exploit hyperspectral data for the analysis of vegetative life forms and communities. As these goals are pursued, many hopes for the application of hyperspectral image data to vegetation mapping remain unrealized, and limitations continue to exist in the current availability and coverage of hyperspectral data. One area that deserves further investigation is the fusion of statistical analysis, environmental gradient modeling, and assessment of spectral reflectance derived from hyperspectral and multispectral sensors for mapping vegetation communities to USNVC standards.

Few researchers have investigated whether the newly adopted USNVC can be used successfully with this approach, and no effort has been attempted to fully incorporate this type of information to map the heavily disturbed vegetation of Shenandoah National Park. If reliable relationships between ecological gradients, spectral reflectance, and vegetation patterns can be established at SHEN, then knowledge of current vegetation distribution, potential successional dynamics, and impacts of future disturbances will be greatly enhanced.

1. 2. Scope of Work

The overall objective of this project was to assess the distribution of vegetation communities in SHEN in relation to ecological units defined by terrain and landscape structure. Supporting and concurrent objectives included 1) classification of vegetation communities into a USNVC hierarchy using data collected at field plots, 2) research and development of ecological gradient models based on terrain analysis, 3) investigations of newly available remote sensing technology for mapping vegetation to the USNVC, 4) construction of a statistical model that predicts the distribution of USNVC vegetation classes from field plots, terrain-based ecological gradient models, and vegetation spectral responses mapped from satellite imagery, 5) delineation of riparian and wetland areas of the park, and 6) statistically valid accuracy assessment of vegetation classifications and ecological models.

The first objective of this project was to evaluate and assess information on distribution and composition of vegetation from current plot databases. Several groups had collected information on vegetation occurrence and distribution within SHEN at the initiation of this project. The VANHP located 103 vegetation plots within the park prior to 2000 and had collected a variety of detailed floristic, structural, and environmental data at each plot. Of these plots, 93 were sampled in the period 1999-2001, just prior to initiation of this project. Shenandoah National Park's research and monitoring effort placed 400 plots throughout the park, stratified by vegetation types predicted from the 1987 vegetation map.

Additionally, USGS-LSC placed over 100 plots in eastern hemlock stands to assess forest composition and tree health in relation to defoliation by hemlock woolly adelgid (*Adelges tsugae*). These data were incorporated in the classification or evaluation process for this project where sufficient data existed to evaluate vegetation community composition and environmental attributes.

Secondly, geographic information system (GIS) based terrain modeling was conducted to determine ecological gradients within the park using landscape and topographic data. We analyzed landscape measures relevant to the occurrence and distribution of vegetation communities (e.g. direct and indirect gradients) from digital elevation models and other GIS data layers such as solar illumination, predicted soil moisture, terrain shape, slope position, and soil parent material (e.g. geology). We used classification and ordination techniques to determine the main ecological gradients within the park that influence vegetation occurrence and distribution. Ecological gradients derived from a digital elevation model (DEM) were used as a framework to assess existing vegetation distribution from field plots, to guide remote sensing interpretations, and to construct predictive models of plant community distributions.

The third objective of this project was to assess the applicability of newly available satellite and aerial imagery for mapping vegetation using the USNVC. Past efforts using moderate spatial and spectral resolution instruments such as Landsat Thematic Mapper (TM) have been successful mapping to broad levels in a classification hierarchy but have had difficulty achieving fine specificity. Newly available imaging technologies offer much higher spectral resolutions (e.g. hyperspectral), or use different approaches for vegetation classification. This project explored the utility of emerging remote sensing methods and instruments for mapping vegetation communities to USNVC through hyperspectral image analysis, statistical classification techniques, and environmental gradient modeling.

The fourth objective was to use statistical modeling techniques to extrapolate vegetation communities observed at field plots to similar environments within the park on the basis of ecological gradient models, spectral responses of current vegetation from satellite imagery, and spatial information on past disturbances. We tested and employed predictive models using Classification and Regression Tree (CART) techniques, canonical correlation, and canonical linear discriminant analysis.

The fifth objective was to put special emphasis on accurately delineating riparian zones through a combination of moisture regime modeling using a DEM and remote sensing assessments. Once predicted riparian and wetland zones were delineated, special emphasis was given to these areas for field assessment and survey.

The last objective was to conduct a statistically valid accuracy assessment of predicted vegetation communities using standard procedures adopted by the national USGS/NPS National Vegetation Mapping program. Two separate field surveys were conducted to assess accuracy of vegetation composition predicted from classifications and gradient models.

1.3. Study Area Description

As of 2004, Shenandoah National Park (SHEN) encompasses 195,821 acres (79,246 ha) of mostly forested uplands in the Blue Ridge Mountains of northwestern Virginia. Of this total, 82,661 acres (33,452 ha) or 42.2% of the park is in Wilderness designation. The park occurs primarily in the “Northern Igneous Ridges” and “Northern Sedimentary and Metasedimentary Ridges” ecoregions of Omernick (Omernick, 1995), although small portions of the park occur in the “Northern Limestone/Dolomite Valleys” and “Piedmont Uplands” ecoregions. Elevations range from a low of 530 ft (161.5 m) near Front Royal to 4,060 ft (1237.5 m) at Hawksbill Mountain. Generally, 14% of the park is in elevations below 1500 ft (457.2 m), 74% in elevations between 1500 ft (457.2 m) and 3000 ft (914.4 m), and 10% is above 3000 ft (> 914.4 m) (Figure 1.1).

The geology of the park consists of three major lithologies: Cambrian-aged siliciclastic rocks of the Chilhowee group (Antietam, Harpers, and Weverton formations); late pre-Cambrian-aged metabasalts (a.k.a. “greenstone”) of the Catoctin formation; and Middle Proterozoic granitic and gneissic rocks, including the Old Rag granite and rocks formerly called the Pedlar formation (alkali-feldspar leucogranite, charnockite, charnockite gneiss, and layered pyroxene granulite) (Figure 1.2). Small areas of the western flank of the park are underlain by Cambrian and Ordivician-aged carbonate rock and calcerous shales of the Tomstown and Waynesboro Formations, and late pre-Cambrian aged siliciclastic rocks of the Swift Run formation occur between the metabasalts of the Catoctin formation and the granitic formations.

Geology and topography are primary drivers of vegetation distribution within the park along with climate, fires, and prior land use history (Conner 1988). Geology and topography act synergistically with climate to influence soil formation, nutrient availability, moisture, solar insolation, and temperature. Siliciclastic parent material of the Chilhowee group produces nutrient poor, well drained, and acidic soils. Metabasalt parent material of the Catoctin formation produces relatively nutrient rich, mesic soils. Granitic and gneissic parent material of the Old Rag granite and former Pedlar formation complex produces intermediate soils of higher acidity than the Catoctin metabasalt. In addition, alluvium deposits occur along stream channels and provide soils of different nutrient and moisture capacity than would be expected from bedrock geology alone. Previous land use history and fire are additional factors that influence vegetation distribution, but are themselves moderated to some extent by geology and topography.

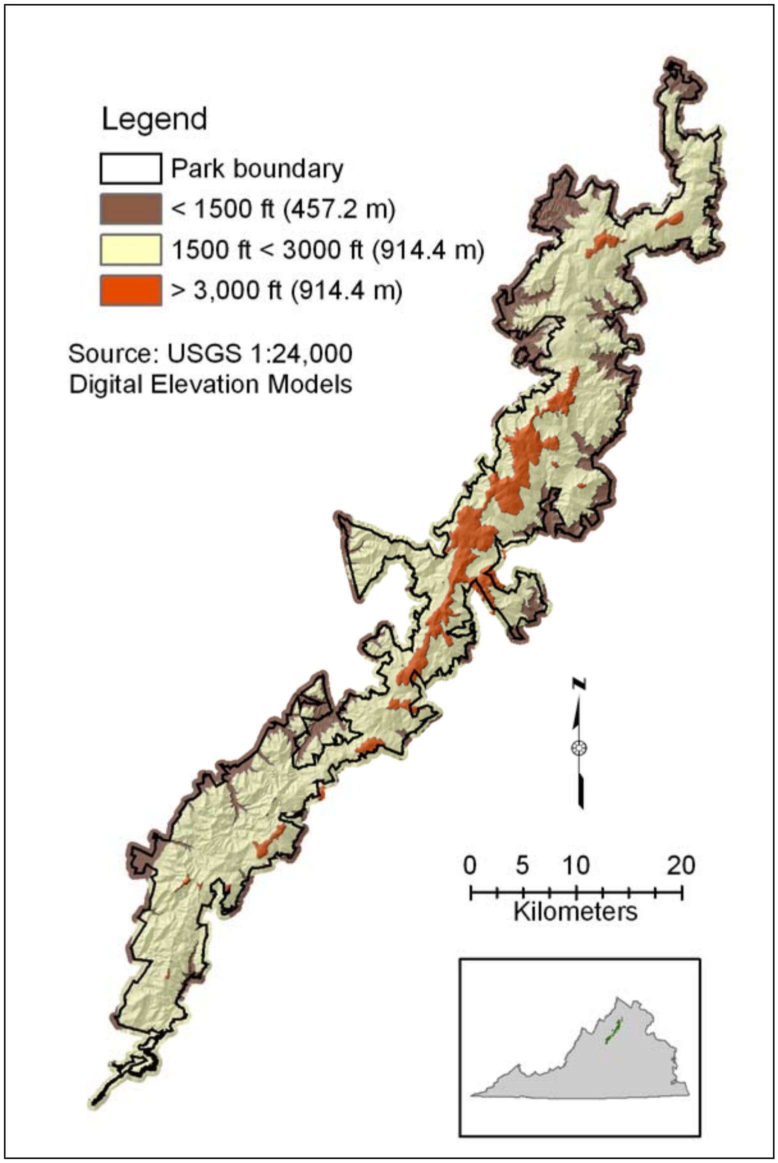

Figure 1.1 Elevation classes of Shenandoah National Park.

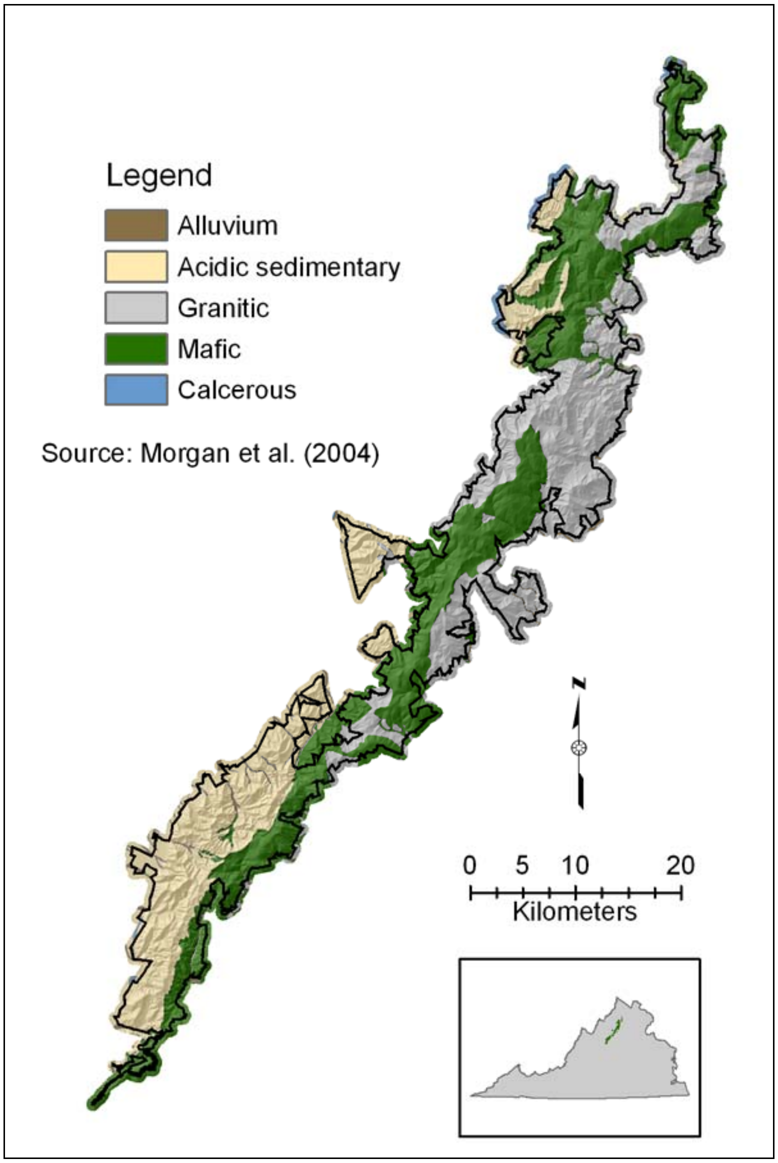

Figure 1.2 Generalized surficial geology of Shenandoah National Park, (after Morgan et al. 2004).

Berg and Moore (1941) recognized the importance of geology in structuring vegetation communities in the park in their extensive mapping effort, but it is unclear how or if this information was used for mapping. While acknowledging that the park was primarily in second growth, they state:

> "Underlying rock formations with residual soil overburden have had a definite influence on the existing forest cover. This influence is evidenced by the Red Oak type associations, which are found generally throughout the moderately moist to moist soils overlying Catoctin greenstone and, less frequently, Hypersthene granodiorite formations; Chestnut Oak types, which prevail on moderately dry to dry aspects underlain by granodiorite and quartzite; and the Bear oak, Scarlet oak, and Pitch Pine types, which are found on the dry to very dry quartzite, shale, and limestone soils…Previously grazed and cultivated lands are confined in general to the more fertile greenstone and granodiorite soils" (Berg and Moore 1941, pg. 2)

Braun (1950) describes the vegetation of the Northern Blue Ridge (including Shenandoah National Park) in relation to the physical landscape. She notes the vegetation of the area as lacking "the luxuriance and variety which are distinctive features of the Southern Appalachian section" due to less favorable climate, lower altitudes, less varied topography, and a greater degree of human disturbance (Braun 1950, pg. 221). Oak-chestnut is described as the prevalent type (even though American chestnut (*Castanea dentata*) was long since extirpated as a dominant canopy species by 1950), and human disturbance was evident in the red cedar (*Juniperus virginiana*), black locust (*Robinia pseudo-acacia*), and sassafras (*Sassafras albidum*) occupying clearings and old fields of the lower slopes (Braun 1950). Braun describes the structure of the upland forests in the park in relation to landscape structure:

> "Forest variations along the upper slopes and crests are related to slope exposure, steepness, and concavity or convexity of slope. Mesophytic red oak-sugar maple-basswood communities or groups of hemlock in northerly concavities alternate with red oak-chestnut communities whose undergrowth contains Azalea, mountain laurel, and blueberries, or with oak-chestnut communities with a continuous heath layer. If the crest is at a low elevation (2500 feet or less) tuliptrees are present in the north slope coves. On windswept slopes and knobs, chestnut oak is abundant, and pines dominate locally…Only at the highest elevations (slopes of Hawks Bill [sic] Mountain) are spruce and fir present." (Braun 1950, pg. 223-224)

Teetor (1988) discussed the limiting effects of elevation, geology, and soil moisture on structuring vegetation communities in the park and recognized the strong influence of disturbance history, but did not specifically incorporate this information into mapping. Instead, she compared the observed vegetation cover types to the "expected topographic distribution" after the fact by assessing vegetation in relation to classes of slope, aspect, and elevation. Topographic influences are discussed by Teetor (1988) to place vegetation cover types in context of the environmental limitations and disturbance history.

Both Berg and Moore (1941) and Teetor (1988) report chestnut oak (*Quercus prinus*) as the dominant cover type occurring on dry, thin soils of the main ridge and spur ridges overlying granitic and siliciclastic geology. However, there is less agreement on both the type and extent of other forest types. Berg and Moore (1941) list red oak (*Quercus rubra*) and scarlet oak (*Quercus coccinea*) as the next most dominant cover types while Teetor (1988) lists yellow poplar (*Liriodendron tulipifera*), red oak (*Quercus rubra*) / ash (*Fraxinus americana*) / basswood (*Tilia americana*) and red oak (*Quercus rubra*) as the next most dominant types. Methodological and classification differences may explain some of the variation between the mapping efforts, but most of the difference must certainly be attributed to 45 years of succession (eg. less open area and more black locust forest cover in the Teetor (1988) map). The difficulty in mapping mixed deciduous forests of the park may also be a factor as evidenced by the accuracy statement of the Teetor (1988) effort: 70% overall accuracy, and between 63% and 74% by-class accuracy.

Knowing that vegetation in SHEN responds predictably to environmental gradients in the absence of disturbance may allow for a predictive approach to mapping by exploiting newly available digital elevation data and satellite imagery

2. METHODS

2.1 Environmental Gradient Modeling

We mapped significant ecological gradients for SHEN as a precursor to vegetation sampling and for use as inputs to predictive models. The overall goal in this effort was to quantify environmental gradients that are important for structuring vegetation communities. Methods used to quantify environmental gradients closely followed those used by other researchers, and made use of geographic information systems (GIS) and digital elevation models (DEM).

A number of researchers have examined vegetation data in relation to environmental gradients derived from digital elevation data (see Table 2.1 for a list of selected recent publications that have examined vegetation in relation to environmental gradients). Important gradients that recur in these studies are: slope direction (e.g. aspect), slope position, slope shape, moisture, light, and (less commonly) rock type, and elevation. We derived environmental gradients following the examples set in these studies to capture gradients important for vegetation growth in the mountains of western Virginia. These are gradients of soil moisture, light, slope orientation (aspect), slope shape, elevation, exposure, and rock type.

We generated information on environmental gradients in two forms, as discrete class maps for use in constructing a map of ecological land units, and as continuous variables for use in predictive modeling of vegetation communities. Both representations were derived using GIS operations.

2.1.1 Ecological Land Units

We followed methods in Anderson and Merrill (1998) for combining gradient layers into an “ecological land units” map (also referred to as a “biophysical units” map). Our goal was to use this information to create sampling strata that capture the range of environments observed. The Anderson and Merrill (1998) method (implemented as a set of GIS scripts by F. Biasi (2001)) builds an ecological units map by classifying and combining individual environmental gradient maps in a GIS. Maps of aspect, moisture, slope, and slope shape are reclassified and assembled to produce maps of landform units. These landform units are then combined with reclassified elevation and geologic maps to produce a final ecological land units or “ELU” map. We used these methods as a guide to building an ecological land units map for Shenandoah National Park, adapting the procedures for local conditions. Individual steps in the process and maps resulting from intermediate and final stages are described.

Table 2.1. Selected publications using environmental gradient models for vegetation community analysis.

Study	Variables considered:
Newell and Peet, 1998 From: "Vegetation of Linville Gorge Wilderness, North Carolina", C. L. Newell and R. K. Peet, Castanea 63(3): 275-322, September 1998. *A species composition and vegetation-environment relationships study.*	- Beer's transformed aspect - Distance to nearest stream - Distance to nearest ridge - Terrain shape index (after McNab) - Topographic complexity - Potential solar radiation (from Solarflux) - Topographic Moisture Index (after Parker)
Anderson and Merrill, 1998 From: " Connecticut River Watershed: Natural Communities and Neotropical Migrant Birds", M.G. Anderson and M. D. Merrill, Final Report, The Nature Conservancy, Eastern Regional Office, Boston, MA, October 15, 1998. *An ecological communities assessment project. Ecological Land Units were derived to assist in a regional planning and assessment project.*	- Slope (degrees) - Moisture Index (after Moore, I.D.) - Landscape position - Lithology - Elevation
Franklin, et. al. 2000 From: "Terrain variables used for predictive mapping of vegetation communities in Southern California", J. Franklin, P. McCullough, and C. Gray, in Terrain Analysis: Principles and Applications, J. P. Wilson and J. C. Gallant, eds., John Wiley and Sons, New York, 2000, pp. 331-353. *A predictive vegetation modeling study.*	- Slope - Aspect - Potential Solar Radiation (from Solarflux) - Upslope catchment area - Topographic wetness - Surface curvature - Distance to stream - Distance to Ridge

The primary data source for environmental gradient analysis was a 10-meter USGS digital elevation model (DEM) for SHEN. This is a compilation of USGS 10-meter resolution 1:24,000 elevation models available for all topographic quads covering SHEN except for the northern-most quad (Front Royal). These data generally improve upon the 30-meter resolution digital elevation data in both surface representation and accuracy. However, these data have artifacts from the source data (contours) that may affect resulting models such as artificial terracing and pits. We resampled the 10-meter DEMs covering the park as well as the 30-meter Front Royal quadrangle to a new 15-meter merged DEM in order to smooth out some of these inconsistencies, and to incorporate data for the

Front Royal quadrangle. This provided a single consistent elevation model covering the park. All elevation-based topographic gradient maps were subsequently derived using this layer.

Elevations from the DEM (originally in meters) were reclassified to correspond to 3 broad elevation ranges: 0-1500 ft (0-457.2 m), 1500–3000 ft (457.2-914.4 m), and greater than 3000 ft (> 914.4 m). These classes were determined to have the greatest correlation with vegetation distribution in the mountains of western Virginia based on previous vegetation assessments (G. Fleming, VANHP, pers. comm.).

Reclassifying the DEM into elevations was accomplished using a simple recode operation. Numeric codes were assigned to correspond to the above classes as follows:

- 0 –1500 ft (0-457.2 m) = 1000
- 1500 – 3000 ft (457.2-914.4 m) = 2000
- > 3000 ft (> 914.4 m) = 3000

We derived an index of topographic moisture from the DEM using methods proposed by Ian Moore (1990) and adopted by Anderson and Merrill (1998) as well as others. The basic idea is to examine the amount of water entering a point on a map (e.g. a pixel) and compare it to the amount of water that would leave the cell based on topography. The “relative moisture index” is computed as the log of the ratio between the flow accumulation at each cell and the slope of the cell. The “flow accumulation” function in ArcInfo (ESRI Inc., Redlands, CA) is used to compute a relative amount of water entering each cell from its upstream neighbors (values are number of upstream cells flowing into each cell). Slope is computed for each cell in the DEM as percent slope. The formula for computation of the moisture index (as given by Anderson and Merrill (1998)) is then:

$$\text{Relative moisture index} = \ln((\text{flowaccumulation} + 1) / (\text{slope} + 1))$$

In order to generalize the map slightly to remove spurious features, we filtered the resulting moisture index map using a mean filter that replaces cell values at each pixel with the mean value occurring in a 3x3 pixel scanning window. Other moisture index maps, such as the Topographic Relative Moisture Index proposed by Parker (1982) could be substituted here if desired.

We derived a landform index using a routine provided by Zimmerman (2000) that computes a terrain shape or landform index in a slightly different manner than that proposed by Anderson and Merrill (1998). Both techniques compute terrain shape in a manner similar to that proposed by McNab (1989) whereby elevations at each pixel are compared to the mean of elevations of neighboring pixels. If the elevation of the focal cell is greater than that of the mean of the neighboring cells, then this is coded as a local high or a convex shaped terrain, while elevations lower than the mean of their neighbors are coded as local lows, reflecting concave shapes. Differing scales of topographic shape can be quantified in this manner by varying the size of the scanning window. Unlike the McNab (1989) method, both the Zimmerman (2000) and the Anderson and Merrill (1998) methods compute a weighted mean of terrain shape from assessments at different spatial scales. We used the Zimmerman (2000) routine since it maintains the terrain shape value for the most influential scale rather than averaging over all scales. The basic calculation implemented in GIS is as follows:

Terrain Shape Index = dem - focalmean(dem, circle, radius (X))

Terrain shape at each pixel on the DEM is calculated as the elevation value at each cell on the DEM minus the mean elevation of pixels in a surrounding circular window of size X, with the scanning window varying from 15 to 150 meters (radius).

We derived aspect (e.g. slope direction) in GIS using a standard routine that classifies slope direction into degrees using compass directions (0-360 degrees). We transformed aspect using Beer's cosine transformation such that slopes facing 50º (described as optimal for southern Appalachian vegetation response by Newell and Peet 1998) are given a value of 2. Other slopes that are within 90° of this optimal NE direction are given a value of 1, and SW facing slopes are given a value of 0.

The formula for computation with ArcInfo is given as:

Beers Aspect = cosine(50° – aspect) + 1

Aspects were further simplified for computation of the ELU units as either N-NE or S-SW. These cutoffs correspond to the perpendiculars to Beer's aspect (eg. 320° and 140°).

Slope was calculated in degrees using standard functions in GIS. Slope is calculated as the maximum angular rate of change (in elevation) of a plane fit to a 3x3 window surrounding each pixel on the DEM (ESRI, 1994).

We also incorporated USGS 1:24,000 digital line graph maps to represent streams, ponds, and wetlands. We converted the hydrologic data into a grid representation that matches the 15 m grid cells of the DEM layer.

We derived landform classes by re-classifying and combining the above maps, following the techniques of Anderson and Merrill (1998) as defined by Biasi (2001). Each map is reclassified into discrete classes and combined in a specific order to derive landform classes. First, slope and landform maps are reclassified and combined. Very steep sloped areas (greater than 35°) are classified as cliffs. Areas of intermediate slope (24° to 35°) are classified as steep slopes. Areas of moderate slope (6° to 24°) are classified as side slopes. Low sloping areas (< 6°) are classified as flats. Terrain shape is used to determine if slopes are concave or convex. Concave slopes are classified as coves or slope bottoms, while convex slopes are classified as upper slopes or side slopes. Flat slopes are classified as either ridge top or bottom, and coded as either moist or dry by overlay with locations of wetlands. Next, aspect maps are reclassified and incorporated into the landform map to determine slopes facing N-NE or S-SW. Finally, streams and lakes are incorporated for the final landform map. The landform map was filtered using a majority filter in a 5x5 pixel window to remove small, spurious landforms.

We initially used a map of geologic formations mapped by Gathwright (1976). However, subsequent to initiation of this project Morgan, et al. (2004) mapped bedrock and surficial geology in SHEN by compiling existing bedrock geology maps (including Gathright (1976) and others) and by compiling maps of surficial geology from existing sources and conducting new mapping at 1:24,000 scale. The updated bedrock geology map uses the most current nomenclature for geologic formations in the area (e.g. it does not split the granitic types into Old Rag and Pedlar formations), and combines some units that inter-grade (Catoctin and Swift Run formations). The updated surficial geology map includes areas of alluvial deposits, debris flows, and depositional (or "strath") terraces. Since this updated map includes additional geologic information not available in the Gathright (1976) map used in the initial analysis, and since the terminology used in coding this map conforms more closely to the latest geologic understanding of SHEN, we used these maps in revised modeling of vegetation composition.

We merged the surficial and bedrock geology maps into a single map and recoded all units to five categories to match the characterization of soil parent material used in the vegetation plot data ordination and classification (Table 2.2, Figure 1.2). Polygons were converted to a grid representation to match the topographic variables. Surficial polygons coded as debris flow or strath terraces were coded in the merged map with the predominant bedrock geology upslope from the surficial unit. Polygons coded as alluvium were not tagged with parent material due to the difficulty in assigning probable parent material. All other areas not covered by a surficial geology polygon as mapped by Morgan, et al. (2004) were coded with bedrock geology type.

Table 2.2. Rock formations and rock type groupings of Shenandoah National Park

Formation	*Rock Type*	*Rock Type Code*
Fluvial deposits	Alluvium	100
Chilhowee Group	Acidic sedimentary (siliciclastic)	200
Quartzo-feldspathic	Granitic (meta-igneous)	300
Catoctin and Swift Run	Mafic (meta-basalt, intergraded conglomerate, slate)	400
Waynesboro, Tomstown	Calcerous/shale	500

In the final step, maps of elevation, landforms, and geology are combined to produce the final ecological land units map. Since the elevation map is coded into the thousands, the geology map is coded into the hundreds, and the landform map is coded into the tens, a simple addition of the three maps results in the final landform class combinations (Table 2.3.)

TABLE 2.3. Class codes for Ecological Land Units map (ELU). Final ELU code is derived by adding codes for elevation, geology, and landform. For example, low elevation-basaltic-cliffs would be coded as 1000+100+10, or 1110.

Elevation		**Geology**		**Landform**	
low (< 1500 ft)	1000	alluvium	100	cliff	10
mid (1500 <= 3000 ft)	2000	acidic sed.	200	steep slope	11
high (> 3000 ft)	3000	granitic	300	slope crest	12
		basaltic	400	upper slope	13
		calcerous	500	flat summit/ridge	14
				sideslope N/NE	20
				cove/ravine N/NE	21
				sideslope S/SW	22
				cove/ravine S/SW	23
				dry flat	30
				slope bottom	33
				stream	40
				lake	42
				spring/seep	43

2.1.2 Environmental Gradient Models for Predictive Modeling

In addition to the discrete maps of ecological land units, we also created continuous maps of environmental gradients to use in predictive modeling. Since vegetation composition grades continuously across the landscape and responds to subtle changes in light availability, nutrients, and soil moisture, maps that capture the continuous gradation of environmental influences are more appropriate for modeling than maps representing gradients as discrete classes.

Guisan and Zimmerman (2000) divide influences on plant growth and distribution into “resource”, “direct”, and “indirect” gradients. Resource gradients are taken up directly by plants (e.g., water, photosynthetic active radiation, and soil nutrients). Direct gradients influence the availability of resource gradients, such as soil type, solar insolation, water availability, and ambient temperature. Indirect gradients represent relatively large-scale influences, such as geology, topography, climate, and latitude, that govern the formation of direct gradients. Typically, indirect gradients (and, less typically, direct gradients) can be created in GIS format for modeling environmental influences over broad areas. Resource gradients are rarely available in spatial format useful for modeling influences on plant communities.

We derived models of direct and indirect environmental gradients using available methods in three general areas: general topographic measures including measures of slope shape, measures of soil moisture, and measures of solar illumination (Table 2.4.) All gradients were derived from the same digital elevation model described in section 2.1.1. Some gradient models were calculated from intermediate steps of the ELU modeling (e.g. Beers aspect transform, slope), while others were calculated using additional specialized scripts.

Table 2.4. Environmental gradients derived for Shenandoah National Park from a 15-meter resolution digital elevation model. A.) Topographic measures B.) Measures of solar illumination C.) Measures of soil moisture

2.4.A. *Topographic Measures*

Derived Gradient	***Derivation***	**Reference**
Elevation (in meters) = height above m.s.l.	DEM	USGS. 1993. *US Geodata, Digital Elevation Models, Data Users Guide*. Technical Instructions: Data Users Guide 5. U.S. Geological Survey, National Mapping Program. Reston, Virginia.
Slope (degrees) = maximum rate of change in z value	Elevation (DEM)	ESRI, Inc. 1994. Cell-based modeling with GRID. Environmental Systems Research Institute, Redlands, CA. 481 pp.
(Measures of Slope Shape)		
Plan curvature = across slope (e.g. horizontal) curvature	Elevation (DEM)	ESRI, Inc. 1994. Cell-based modeling with GRID. Environmental Systems Research Institute, Redlands, CA. 481 pp.
Profile curvature = down slope (e.g. vertical) curvature	Elevation (DEM)	ESRI, Inc. 1994. Cell-based modeling with GRID. Environmental Systems Research Institute, Redlands, CA. 481 pp.
Terrain shape index (TSI) = local convexity or concavity	Elevation (DEM)	McNab, H.W. 1989. Terrain shape index: Quantifying effect of minor landforms on tree height. Forest Science 35(1): 91-104.
Relative Slope Position (RSP) = position on slope relative to stream and ridgeline	Elevation (DEM)	S. P. Wilds. 1996. Gradient analysis of the distribution of flowering dogwood (*Cornus florida L.*) and dogwood anthracnose (*Discula destructiva Redlin*.) in western Great Smoky Mountains National Park. M.S. Thesis, Univ. of North Carolina,Chapel Hill. 151pp.

2.4.B. *Measures of Solar Illumination*

Derived Gradient	***Derivation***	**Reference**
Beer's Aspect = slope direction (aspect) converted to a continuous scaled variable, set to maximum for NE slopes (45° = coolest slope).	Aspect in degrees	Beers, T.W., Dress, P.E., and Wensel, L.C. 1966. Aspect transformation in site productivity research. J. For. 64:691.
Average Solar Illumination = relative amount of sunlight striking the surface throughout the year.	Elevation (DEM) (sun position at solstices and equinoxes)	ESRI, Inc. 1994. Cell-based modeling with GRID. Environmental Systems Research Institute, Redlands, CA. 481 pp.

2.4.C. *Measures of Soil Moisture*

Derived Gradient	***Derivation***	**Reference**
Topographic Relative Moisture Index (TRMI) = a summed scalar index of relative moisture availability based on aspect, slope, slope shape, and relative slope position	Aspect Slope Plan curvature Profile curvature RSP	Parker, A.J. 1982. The topographic relative moisture index: an approach to soil-moisture assessment in mountain terrain. Phys. Geogr. 3(2):160-168.
Relative moisture index (RMI) = relative amount of water flowing into a pixel (flow accumulation) in relation to amount flowing out based on slope (a.k.a. "wetness index")	Elevation (DEM)	Moore, I.D, Gessler, P.E., Nielsen, G.A., and Peterson, G.A. 1993, Soil attribute prediction using terrain analysis. Soil Science Society of America Journal 57:443-52.
Topographic convergence index (TCI) = similar to wetness index but calculates the upslope contributing area in relation to slope expressed as percent rise	Elevation (DEM)	Wolock, D.M., and G.J McCabe, Jr. 1995. Comparison of single and multiple flow direction algorithms for computing Topographic parameters in TOPMODEL. Water Resources Research 31:1315-1324.
Compound topographic index (CTI) = a steady state wetness index very similar to TCI except the tangent of slope is used rather than rise/run.	Elevation (DEM)	Moore, I.D, Gessler, P.E., Nielsen, G.A., and Peterson, G.A. 1993, Soil attribute prediction using terrain analysis. Soil Science Society of America Journal 57:443-52.

2.2 Sample Site Selection

2.2.1 ELU-based Sample Site Selection

We located new sampling sites to build the vegetation classification scheme and to serve as training data for mapping. Sample sites were stratified within Ecological Land Unit types proportional to the area that each type represented in the park. We determined that we could sample vegetation at a maximum of 500 field sites during the life of the project through discussion between personnel from USGS-LSC, VANHP, and NPS. We initially focused sampling only on the basaltic, siliciclastic, and granitic rock types since these units form the majority of the park by area and some sites on the carbonate bedrock of the western flank of the park had already been sampled by VANHP prior to initiation of this project. The proportion of area in each ELU was multiplied by 500 to get the number of initial sample points to place in each ELU. Within each ELU, points were randomly located using a specialized script written for Arc/Info GIS. Locations were filtered such that they were at least 100 meters, but no more than 500 meters, from a road or trail to avoid areas likely to be influenced by human land use and to improve access to sample sites, respectively. In addition, sample points were restricted to areas at least 20 meters from an ELU boundary to avoid sampling in edge habitats.

Selected sample site coordinates were exported along with a unique point number and ELU type as an ASCII text file. Sample site coordinates were loaded into (non-differential) Global Positioning System (GPS) units for field navigation. Sample points were located in the field to within 5-10 meters (on average) of their predetermined location. In some cases, pre-selected sample sites were found in the field to be in heavily disturbed vegetation (e.g. open canopy with dead or downed trees and thick shrub succession). In these cases, a judgment was made in the field by VANHP botanists as to whether the disturbance was severe enough to alter the vegetation composition. Plot locations with subjectively determined severe disturbance were relocated in the field to the closest intact vegetation within the same ELU.

2.2.2 Riparian and Wetland Sample Site Selection

Several ELU strata individually represented less than 0.1% of the park in area. Due to the small size of these units and limited resources, generally no samples were placed in these units. However, in order to meet the objective of assessing and mapping wetland areas, we paid special attention to riparian and wetland site selection in 2002. Since wetland and riparian areas represent only a small proportion of area in the park as opposed to upland areas, we added additional effort out of proportion to the numbers of samples expected from the ELU-based sample allocation. We selected an initial sample for 2002 that included at least 3 randomly selected sample plots in each wetland and riparian ELU type found in the park.

2.3 Field Survey Methods

2.3.1 Field Data Collection:

Plots were sampled using the relevé method (sensu Peet et al. 1998), following standard VANHP procedures. As a rule, 400 m^2 quadrats with 20 x 20 m configurations were employed in forest and woodland vegetation, while 100 m^2 quadrats with 10 x 10 m configurations were used in shrubland and herbaceous vegetation. At some plots, however, rectangular configurations (e.g., 16 X 20 m, 10 x 40 m, or 5 x 20 m) were used to conform with narrow vegetation zones of cliffs, ridge crests, ravines, and stream bottoms. In three cases, rocks, downfalls, and other impediments made it impractical to sample anything larger than a 200 m^2 plot. Vegetation sampling under this project was conducted during the growing seasons of 2001, 2002, and 2003 and data were collected from 208 plots. Data from 103 additional plots sampled in the park by VANHP during the period 1990-2000 were also utilized in the analysis. Of these plots, only 10 sites were sampled prior to 1999, and therefore most sites were contemporaneous with conditions encountered during 2001-2003 field sampling.

2.3.2 Vegetation Measurements:

To the extent possible, plots were placed in homogeneous stands of vegetation. Every vascular plant taxon present was recorded and its cover, defined as the percentage of the ground covered by the vertical projection of above-ground biomass, was visually estimated over the full plot area. Cover was assigned using a nine-point scale of cover classes (Table 2.5).

The overall cover of mosses, lichens, and liverworts was estimated, but the individual covers of non-vascular taxa were not estimated. Vascular plants thought to be characteristic of the sampled community, but located outside the plot, were recorded parenthetically if visible from the boundary, and assigned a cover class score of "p." The total vegetative cover was also estimated using the same nine-point cover-class scale used to estimate species covers.

Table 2.5. Cover class scores used in field sampling and data analysis (400 m^2 plot).

Cover Class:	Percent Cover Range:	Area of Coverage:	Cover Class Midpoint (%):
(p)	present outside plot	-	0.05
1	< 0.1%	< 20 cm^2	0.05
2	0.1% to 1%	20 cm^2 to 4 m^2	0.55
3	1 to 2%	4 m^2 to 8 m^2	1.50
4	2 to 5%	8 m^2 to 20 m^2	3.50
5	5 to 10%	20 m^2 to 40 m^2	7.50
6	10 to 25%	40 m^2 to 100 m^2	17.50
7	25 to 50%	100 m^2 to 200 m^2	37.50
8	50 to 75%	200 m^2 to 300 m^2	62.50
9	75 to 100%	300 m^2 to 400 m^2	87.50

In addition to recording presence and cover for all species, stand structure was quantified by measuring the size distribution and vertical stratification of woody plants. Each woody stem (trees, shrubs, lianas) ≥ 2.5 cm dbh and < 40 cm dbh was tallied within 5 cm diameter classes, using the measurement of the stem at breast height (1.4 m). Diameter at breast height (dbh) classes used were 2.5-5, >5-10, >10-15, >15-20, >20-25, >25-30, >30-35, and >35-40 cm. Stems ≥ 40 cm dbh were individually measured to the nearest 1 cm. The maximum canopy height was measured using a clinometer and the cover of each woody species was estimated (if present) at each of six height strata:

- herb layer, < 0.5 m
- shrub layer, > 0.5 to 6 m
- tree layer, > 6 to 10 m
- tree layer, > 10 to 20 m
- tree layer, > 20 to 35 m
- tree layer, > 35 m

2.3.3 Environmental Measurements:

A standard set of environmental data was measured or estimated at each plot (Table 2.6). Slope inclination and aspect were measured to the nearest degree from plot center. In plots with variable microtopography, slope was measured at several points and averaged. Elevation was determined to the nearest 10 ft (~ 3 m) using a topographic map or altimeter. The percent cover of different surface substrates was estimated visually, with precision varying such that values summed to 100%. Topographic position, slope shape (both horizontally and vertically), soil drainage class, soil moisture regime, and inundation were assessed using scalar values. Bedrock geology was determined to the greatest precision possible by using existing geological maps, while the characteristics of surface rocks present in a plot were recorded in the field.

Soil samples were collected from the top 10 cm of mineral soil (below the surficial litter and humus) at 288 plots. Mineral soil was absent, or not possible to collect, at 23 plots located on rock outcrops or boulderfields. As a rule, soil was collected from several locations within a plot and mixed into a composite sample. Depth of surface duff, soil color, and texture were evaluated in the field and recorded on the plot forms. Soil samples were oven-dried, sieved (2 mm), and analyzed for pH, phosphorus (P), soluble sulfur (S), exchangeable cations (calcium [Ca], magnesium [Mg], potassium [K], and sodium [Na] in ppm), extractable micronutrients (boron [B], iron [Fe], manganese [Mn], copper [Cu], zinc [Zn], and aluminum [Al], in ppm), total exchange capacity (CEC; m.e.q./100 g), total base saturation (%TBS), and percent organic matter (%OM). Chemical analyses were conducted by Brookside Laboratories, Inc., New Knoxville, Ohio. Extractions were carried out using the Mehlich III method (Mehlich 1984) and percent organic matter was determined by loss on ignition.

Evidence of any past or ongoing disturbances, including but not limited to logging, fire, exotic plants, erosion, grazing/browsing, wind or ice damage, hydrologic alterations, chestnut blight, dogwood anthracnose, southern pine beetle, gypsy moth, and hemlock woolly adelgid, was recorded from each sample site.

2.3.4 Sample Site Metadata:

Standard metadata, or information regarding the implementation of the sampling protocol, were recorded at each plot. These included plot numbers, date(s) of sampling, participants, geopolitical locality (county/city), survey site name, USGS quadrangle, plot size and configuration, photographic documentation, and a written description of the plot location. Plots were assigned unique alphanumeric codes. A global positioning system (GPS) unit was routinely used to record locational data with greater precision. For plots established prior to 2000, the UTM (Universal Trans Mercator) coordinates of each plot location were determined to 10 m (~ 33 ft) precision using either GPS or by using ArcView GIS

(Version 3.2; ESRI 1999), and all plot locations were mapped as precisely as possible on USGS 7.5’ quadrangle maps. Plots established after 2000 were mapped in the field using GPS receivers. Plot coordinates were either differentially corrected or averaged from 30+ non-differentially corrected positions. Accuracy of the post 2000 plot coordinates is estimate to be < 10 m (~ 33 ft).

Table 2.6. Topographic / hydrologic environmental indices recorded at each plot-sample site (from protocol established by VANHP).

Topographic position:
- A – plain / level
- B – toe
- C – lower slope
- D – middle slope
- E – upper slope
- H – crest
- I – basin / depression

Surface Substrate: % cover
- decaying wood
- bedrock
- boulders and stones
- gravel and cobbles
- mineral soil / sand
- litter / organic matter
- water
- other

Measured Slope (degrees)

Slope shape

Vertical
- C – concave
- X – convex
- S – straight

Horizontal
- C – concave
- X – convex
- S – straight

H – hummock and hollow microtopography
I – irregular craggy/bouldery microtopography

Measured Aspect

______ degrees
F (flat)
V (variable)

Soil Drainage Class:
- A – very poorly drained
- B – poorly drained
- C – somewhat poorly drained
- D – moderately well drained
- E – well drained
- F – rapidly drained

Inundation:
- A - never
- B - infrequently
- C – regularly, for < 6 mos.
- D – regularly, for > 6 mos.
- E – always submerged by shallow water (< 30 cm)
- F – always submerged by deep water (> 30 cm)

Soil Moisture Regime:

A – very xeric (moist for negligible time after precipitation)
B – xeric (moist for brief time)
C – somewhat xeric (moist for short time)
D – submesic (moist for moderately short time)
E – mesic (moist for significant time)
F – subhygric (wet for significant part of growing season; mottles at < 20 cm)
G – hygric (wet for most of growing season; permanent seepage / mottling)
H – subhydric (water table at or near surface for most of the year)

I – hydric (water table at or above surface year round)

Hydrologic Regime:

Terrestrial (*i.e.*, not a wetland)
Non-Tidal
- A – Permanently flooded
- B – Semipermanently flooded
- C – Seasonally flooded
- D – Intermittently flooded
- E – Temporarily flooded
- F – Saturated

2.4 Plot Data Analysis and Classification Methods

2.4.1 Data Preparation and Transformation:

Stem diameter measurements were used to compute density (stems/ha) and basal area (m^2/ha) for all woody plants at each plot. Basal area was calculated by multiplying the geometric mean of each diameter class by the density of stems within that class. Density and basal area were used to calculate importance value, defined as the average of relative density and relative basal area for each species.

Prior to analysis, most environmental variables were transformed, either to normalize frequency distributions or to assign numeric values to categorical variables. Topographic position, slope shape in vertical and horizontal directions, and soil moisture regime were converted to ordinal variables (Table 2.7). While the resulting absolute values of these variables are arbitrary, the rank orders of values correspond to putative underlying environmental gradients. Aspect was transformed using the cosine method of Beers *et al.* (1966), using the formula $A' = \cos(45^{\circ} - A) + 1$, where A' = transformed aspect and A = aspect in degrees. This transformation standardizes aspect to a linear variable from 0 (225º; SW, dry, solar-exposed) to 2 (45º; NE, moist, sheltered), and can be used as a surrogate variable for topographic moisture and solar exposure.

Surface substrate values were converted to decimals and arcsine transformed to normalize their distributions. Since the values for all substrate classes sum to 100 and thus each can be defined as a linear combination of the others, a non-vascular (bryophyte and lichen) substrate cover was added to eliminate collinearity in surface substrate for most plots. Values for all soil variables except pH were natural log-transformed to normalize their distributions and make the values more biologically interpretable (Palmer 1993). A synthetic fertility index (CEC x TBS/100) was also calculated for each plot.
Horizontal and vertical slope shape was also converted to a single ordinal variable (scale = 0 to 10) using a modification of Parker (1982) (Table 2.7).

A synthetic Topographic Relative Moisture Index (TRMI) was calculated for each plot using a procedure modified from Parker (1982). TRMI is a scalar ranging from 0 (lowest moisture potential) to 60 (highest moisture potential) and combining four topographic variables that potentially influence water runoff, evapotranspiration, and soil moisture retention:

- Slope inclination (10-point scale; per Parker [1982])
- Slope shape (10-point scale; as above)
- Aspect (20-point scale) = Beers-transformed aspect x 10
- Topographic position (20-point scale) = (1-relative slope position) x 20

Table 2.7. Ordinal variables used in analysis for scalar topographic and soil moisture variables estimated in the field.

Topographic Position

- I - basin/depression = -1
- A, J, K - plain/level, floodplain, stream bottom = 0
- B - toe = 1
- C - lower slope = 2
- D, G = middle slope, ledge/terrace = 3
- E, F = upper slope, escarpment/face = 4
- H = crest = 5

Soil Moisture Regime

- A - very xeric = 1
- B - xeric = 2
- C - somewhat xeric = 3
- D - submesic = 4
- E - mesic = 5
- F - subhygric = 6
- G - hygric = 7
- H - subhydric = 8
- I - hydric = 9

Slope Shape - Vertical and Horizontal

- C - concave = -1
- X - convex = +1
- S - straight - 0

Slope Shape Index (SLSHI)

vert. profile	horiz. profile	SLSHI
concave	concave	10
concave	straight	9
straight	concave	7
straight	straight	5
straight	convex	3
convex	straight	2
convex	convex	0

Because mapped bedrock formations of Shenandoah National Park are somewhat heterogeneous and contain similar lithologic units, each plot was assigned to one of four aggregate geological classes (Table 2.8) based on the prevalent surface rocks at the site; if no surface rocks were present, the assignment was based on the mapped bedrock unit. Geologic substrate was used in subsequent quantitative analyses by defining dummy (binary) variables for classes 2, 3, and 4, with class 1 as the reference (ter Braak and Looman 1995).

Table 2.8. Aggregate geological classes used as dummy variables in data analysis.

No.	Aggregate Geological Class:	Definition and relationship to formations mapped by Rader and Evans (1993)[1]:
1	Alluvium	heterogeneous, bouldery and cobbly stream-bottom alluvium derived from and underlain by various formations
2	Acidic Sedimentary	outcrops and debris of quartzite, metasandstone, metasiltstone, and phyllite prevalent in **Єch** and **Zsr**
3	Granitic	outcrops and debris of charnockite, charnockite gneiss, granite, leucogranite, granulite, and related rocks in **Yal**, **Yc**, **Ycm**, **Yor**, and **Ypg**
4	Mafic	outcrops and debris of metabasalt prevalent in **Czc**

[1] Names of formations:

Єch –Chilhowee Group (Antietam, Harpers, and Weaverton Formations)
ЄZc – Catoctin Formation
Yal – Leucogranite
Yc – Charnockite
Ycm – Chanockite Gneiss
Yor – Old Rag Granite
Ypg – Layered Pyroxene Granulite
Zsr – Swift Run Formation

Botanical nomenclature generally follows Kartesz (1999). As a rule, taxa were treated at the highest level of resolution possible, but the identification of varieties and subspecies was not always possible. A few taxa identified only at generic or higher levels (*e.g.*, "*Carex* sp." or "unidentified woody seedling") were deleted prior to analysis.

2.4.2 Cluster Analysis:

Hierarchical, agglomerative cluster analysis, implemented in the software program PC-ORD (version 4.17; McCune and Mefford 1999), was employed to identify compositionally similar groups and generate a classification from the combined 311 plot data set. During preliminary analyses, the Lance-Williams Flexible-Beta linkage method (Lance and Williams 1966, 1967) was used in conjunction with the Bray-Curtis coefficient of community (Bray and Curtis 1957) to identify major groups in the data set. Based on these analyses, the full data set was divided into six subsets containing, roughly, plots of 1) acidic forests, 2) high-elevation forests, 3) low-elevation rich forests, 4) mesic and dry mesic mixed forests, 5) rock outcrops, and 6) non-alluvial wetlands. Additionally, six compositionally unique or heterogeneous plots were identified as outliers and removed from the analysis.

Subsequent cluster analyses were conducted on each of the six groups using three data treatments: 1) raw cover class scores, 2) cover class scores relativized by site totals, and 3) cover class scores relatived by species maxima. Moreover, analyses using each data treatment were run with two different dissimilarity measures: the Bray-Curtis coefficient and Chord Distance (relativized Euclidian distance). A beta setting of –0.5 was used in all analyses. All six combinations of data treatments and clustering strategies performed similarly in the analyses of each subset, producing dendrograms with similar major divisions and plot groupings and a high percentage of plots with the same finer-level group memberships. After examining the results from all six protocols, the most ecologically interpretable dendrogram for each subset was accepted (Appendix 1).

2.4.3 Compositional Summary Statistics:

Compositional statistics were calculated to evaluate the adequacy of groups recognized in cluster analysis and ultimately to assist in naming and describing the community types. Initially, total mean cover and total frequency across all 311 plots were determined for every taxon. Cover class scores were converted to the midpoints of their respective percent ranges, the midpoints were averaged, and resulting values were back-transformed to cover class scores. For each taxon in each group under consideration, the following summary statistics were then calculated:

- **Frequency** – the number of samples in a group in which a species occurs.
- **Mean Cover** – back-transformed cover class value corresponding to mean percent cover calculated from midpoint values of cover class ranges. All samples assigned to a group were considered when calculating mean cover, not just those in which a taxon was present; absences were assigned a cover value of 0.
- **Relative Cover** – the arithmetic difference between mean cover (for a given group of samples) and total mean cover (for the entire data set) (= Mean Cover – Total Mean Cover). Expressed by plus or minus symbols, this value provides a *relative* approximation of how much more, or less, abundant a particular species is in a community type compared to the overall data set.
- **Constancy** – the proportion of samples in a group in which a species occurs, expressed as a percentage (= [Frequency / Number of samples in group] x 100). Because they are scaled to 100, constancy values can be compared across community types with unequal numbers of plots.
- **Fidelity** – the degree to which a species is restricted to a group, expressed as the proportion of total frequency that frequency in a given group constitutes (= [Frequency / Total Frequency] x 100). An accidental or exotic species can have maximal (100) fidelity to a type if it occurs in only one sample in the entire data set. As a result, fidelity alone can perform poorly as a criterion for identifying characteristic species and distinguishing among types.
- **Indicator Value** (IV) (= [Constancy x Fidelity] / 100). A synthetic value indicating species that are both frequent within and relatively restricted to a group of plots.
- **Indicator Value Adjusted by Cover, Scaled** (Scaled Adj IV) (= [Indicator Value x Mean Cover] / 9). By dividing IVxMC by 9, the maximum possible cover value, this statistic synthesizes information about frequency, diagnostic value, and mean abundance. A species entirely restricted to a particularly community type, occurring in every sample of that type, and attaining maximum mean cover will have a Scaled Adjusted IV of 100 for that type. Empirically, taxa with Scaled Adjusted IVs ≥ 15 are almost always those most characteristic of a

type, although the exact range of values in any given type or data set may vary considerably.

- **Indicator Value Adjusted by Cover, Unscaled** (Unscaled Adj IV) (= Indicator Value x $2^{\text{relative cover}}$). An alternative, unscaled synthetic measure of adjusted IV, using relative cover as the modifier of IV. Since cover classes form a logarithmic, rather than linear scale of values, Unscaled Adjusted IV is a statistically more legitimate means of incorporating information on cover, and has the advantage of not favoring only dominant species and better identifying species that are considerably more abundant within a given type than in the data set as a whole. This statistic is sensitive, however, to vegetation types containing few samples and to species with low overall frequency.

Additionally, the following statistics were generated for each group:

- **Mean Species Richness** – the average number of species present per plot (*S*); only species rooted inside plot boundaries were included in this calculation.
- **Homoteneity** – the mean constancy of the *S* most constant species, expressed as a fraction. This value (sensu Curtis 1959) can be considered the constancy of the average species in a community type; higher values for homoteneity indicate greater uniformity in species composition among plots. Although homoteneity is not independent of group size, often increasing as the number of group members decreases, it can be used to evaluate whether community types have been defined at an appropriate level.

These procedures were used to efficiently evaluate a sizeable number of groups in the competing dendrograms generated by different cluster analysis protocols. Several problematic plots which shifted among multiple groups depending on the clustering protocol used were ultimately assigned to one group by evaluating the statistical interpretability of each affected group with and without the questionable plot, and by examining the position of the plot on the axes of non-metric multidimensional scaling ordinations.

2.4.4 Community Type Structural Characterization:

The standard forestry statistics calculated for each plot (see section 2.3.2) representing a community type were averaged to obtain a composite characterization of woody vegetation for that type. In addition, the typical vertical structure of each community type was determined by averaging cover class scores of all woody species in each stratum across all plots representing the type. Similarly, mean canopy height for a community type was obtained by averaging the canopy height measurements from all representative plots.

2.4.5 Environmental Summary Statistics:

Mean values for continuous and ordinal environmental variables were calculated for each group to aid in describing community types and identifying the differences between them. These calculations were performed with raw (untransformed) values, which were averaged across all plots representing a given group. Mean aspect was calculated as the average position along an arc defined by the range of aspect values.

2.4.6 Ordination:

The ordination method non-metric multidimensional scaling (NMDS; Kruskal 1964) was used to validate the classification, detect compositional variation and trends that are obscured in cluster analysis, and aid in identifying the environmental gradients along which vegetation classes and community types are distributed. NMDS is a type of indirect gradient analysis that assigns samples to coordinates in ordination space in a way that maximizes, to the extent possible, the rank-order (*i.e*., non-parametric) correlation between inter-sample distance in ordination space and inter-sample dissimilarity (*i.e.*, ecological distance; Minchin 1987). Ordination studies of each major compositional group identified in cluster analysis, as well as of selected smaller groups of closely related community types, were conducted (Appendix 1). NMDS was implemented in PC-ORD (version 4.17; McCune and Mefford 1999). The Bray-Curtis index was used to calculate dissimilarity and VARIMAX rotation was employed to optimize axis placement in all ordination studies for this project. Each ordination was computed using 40 random starting configurations, and configurations with the lowest stress levels were used for interpretation.

Based on preliminary plots of stress vs. dimensionality, most ordinations were extracted in three dimensions. Two-dimensional ordinations were used to examine compositional variation within a few of the smaller groups. Pearson correlations between environmental variables and sample coordinates on each axis were calculated, and significant correlations were displayed through joint plot overlays. Environmental variables used in ordination analyses were ordinal variables for slope shape; continuous variables for arcsine-transformed surface substrate values, Beers-transformed aspect, slope, elevation, raw and natural log-transformed soil chemistry values; topographic relative moisture index (TRMI), and dummy variables for geologic substrate. After preliminary studies, the ordinal variable representing soil moisture regime was eliminated from the analysis since it is redundant with, and less objective than, the synthetic TRMI scalar.

2.4.7 Assignment of Classified Vegetation Types to the U.S. National Vegetation Classification (USNVC) System:

Once the classification was finalized, the classified vegetation types were subjectively compared to existing units of the USNVC (Grossman et al. 1998, Anderson et al. 1998, NatureServe 2002). All Shenandoah types were either assigned to a conceptually similar USNVC type, or used as the basis for a new USNVC unit. The global USNVC descriptions for existing types were edited, and global descriptions for new types were written. Local park descriptions were written for all classified types. During this process, the global and state conservation ranks of each existing type were re-evaluated and modified if needed, and all new types were ranked.

2.4.8 Development of Field Key to Shenandoah National Park Vegetation Types:

A draft dichotomous key for field identification of classified types was prepared by NatureServe ecologists based on descriptions written by VANHP. It was subsequently reviewed and modified by VANHP, and the final key was produced after two days of field-testing in the park.

2.5 Image Processing and Classification

2.5.1 Hyperspectral Imagery:

Hyperspectral images from NASA's AVIRIS platform were acquired for this research. Two high altitude AVIRIS images were collected from NASA ER-2 aircraft, one on 14 May 2000 and another on 13 July 2001. High altitude AVIRIS pixels have approximately 17 m spatial resolution and 224 bands at 10 nm intervals between 400-2500 nm.

AVIRIS images were converted to reflectance, corrected for atmospheric effects, and referenced to UTM map coordinates as described here. AVIRIS image processing consisted of reading raw image data for four flight lines, two flight strips per date to cover the extent of SNP. Each raw image strip showed a cross-track illumination effect due to the bi-directional reflectance (BRDF) properties of forest canopies and properties of the scanning AVIRIS sensor. This brightness gradient was corrected using a tool in ENVI that fits a trend line to the mean cross-track values for each band and then adds or subtracts the correction factor at each cross-track pixel for each band. This method effectively removes the dominant brightness gradient present in the raw image strips.

Cloud cover of different types was an issue in the hyperspectral image analysis, as it can obscure or attenuate the reflectance of desired target areas. Both AVIRIS images were affected by some cloud cover over parts of Shenandoah National Park, though clouds were a larger problem for the summer image. The image strips from 13 July 2001 had some coverage of cumulous clouds, interfering with vegetation map creation. Unlike other types of clouds that completely obscure the ground and create dark shadows, high cirrus clouds are partially transparent and can contaminate image pixels by increasing the brightness of the reflectance target in ways that are difficult to detect. Subtle differences in cirrus cloud contaminated pixels could hamper modeling efforts by adding atmospheric variation to pixel reflectance and obscuring variation due to vegetative composition and structure. The May AVIRIS image for this analysis had some high cirrus clouds that were affecting reflectance, predominantly at the northern and southern ends of the image strips. These images were corrected using a method developed by Gao et al. (1998) to remove high cirrus cloud effects in AVIRIS imagery. The correction uses a relationship between apparent reflectance at 664 nm (band 34) in the range of red visible light and reflectance centered at 1374 nm (band 109), an atmospheric absorption window; the relationship between these wavelength bands highlights the presence of high cirrus clouds. A correction factor is derived by subtracting the slope of the regression equation from the apparent reflectance at 1374 nm. This factor is then subtracted from the apparent reflectance of each pixel at each wavelength band. This method was developed to correct only bands from 400-1000 nm in wavelength, and thus was used to correct only bands 1-41 in the spring AVIRIS image only.

After removing the brightness gradient from images for both dates and the cirrus cloud effects from the May 2000 image strips, each image strip was corrected for atmospheric effects and converted to reflectance using the ACORN software package. In order to transform the raw image strips into map coordinate space, several hundred ground control points (GCP's) were collected from the image strips and corresponding digital USGS topographic quad grids for the entire park. A total of 297 GCP's were collected for the May 2000 AVIRIS images and 349 were collected for the July 2001 images. A triangulation method, also known as rubber sheeting, was used to warp the image to UTM coordinates, zone17, NAD83. Image irregularities in the raw imagery that resulted from the pitch and yaw of the aircraft made a polynomial transformation method ineffective. Triangulation is used when polynomial transformations are not possible and is most accurate with a dense coverage of GCPs. Geocorrected image strips were mosaicked into image mosaics for each date to produce the base image files for the vegetation mapping analysis.

2.5.2 Landsat TM Imagery:

In addition to hyperspectral imagery, a time-series of Landsat TM images from five dates was also used to test the ability of multi-temporal Landsat data to map forest associations. The results of this analysis would be used to fill in small portions of Shenandoah National Park that were not covered by AVIRIS image data (see Figure 3.6). The time-series included three early spring images: 12 April 1984, 26 May 2000, and 24 May 2002, and two early fall images: 19 September 1984 and 5 September 2002. These dates were selected to take advantage of the variable reflective properties of young leaves in spring and older leaves late in the growing season. The images from 1984 were included because they were taken before several major disturbances affected the park, including gypsy moth defoliation, hemlock woolly adelgid defoliation, and large-scale fires. Images from 2002 were used to incorporate the lasting effects of these disturbances in the predictive model of vegetation distribution. It was left to the statistical analysis to determine which predictive variables were most adept at discriminating current vegetation conditions as seen in the field data, and to weight those predictors accordingly. Each Landsat image was converted to planetary reflectance and geometrically corrected to UTM map coordinates. Landsat images were spatially accurate to within 30 m. Reflectance values from TM bands 1-5 and 7 for each date (a total of 30 bands) were extracted as described above and used in the canonical linear discriminant analysis.

2.5.3 Aerial Photography:

We acquired aerial photography as a reference source for interpreting vegetation community types from satellite and hyperspectral imagery. We contracted with an aerial photography firm (Air Photographics Inc., Martinsburg, WV) to acquire 1:24,000 scale color infrared photography over the park during leaf-on conditions in late-August and early September 2001. Flights were flown with 60% overlap and 30% sidelap resulting in 213 exposures delivered as color transparencies. Of the 213 aerial photos imaged, only 156 are needed to completely cover the park, the remaining 57 duplicate areas covered inside the park or are wholly outside the park boundary. We had 156 images covering the park scanned at 800 dpi by a commercial firm (Spectrum Mapping LLC, Easton, MD) and delivered as digital files in TIFF format. These images were orthorectified by USGS-LSC to a topographic base using Erdas Imagine Orthobase software in a block triangulation process. Output images are referenced to a Universal Transverse Mercator (North American Datum of 1983) projection at 1-meter pixel resolution. Average positional error of the orthorectified imagery is 2.4 meters (root mean square error). Images were stored both individually and as collar-clipped mosaics by 1:12,000 quadrangle.

We also compiled 1:12,000 digital orthophotography from the USGS Digial Orthophoto Quarter Quardrangle (DOQQ) dataset as a reference source. The data covering Shenandoah National Park were acquired by the USGS National Mapping Division during leaf-off conditions in 1994 and 1997, and orthorectified to 1-meter pixel resolution. Average stated positional error of this dataset is 2.3 meters RMSE.

2.5.4 Model Training Data:

Four reflectance spectra were extracted from the hyperspectral and multispectral images for an area surrounding each of 305 vegetation plot locations using GPS coordinates. These spectral samples covered an area of approximately 0.12 ha (0.30 acres) around each plot for the AVIRIS analysis and 0.36 ha (0.89 acres) for the Landsat analysis. The resulting spectral "bundles" were linked without averaging to their respective forest plot data and used to map forest associations developed from the field data. Figure 2.1 illustrates the spectral response recorded by the AVIRIS sensor in May 2000 at 3 plots, with 4 bundles of samples each. Due to AVIRIS image extents, not all of the plot data overlapped the image data. Two hundred thirty-three (233) plots overlapped the 13 July 2001 AVIRIS image mosaic and 265 plots overlapped the 14 May 2000 AVIRIS image mosaic for a total of 932 and 1060 spectral samples, respectively. Some regions of hyperspectral bands were excluded from the statistical analysis due to noise and atmospheric interference. For AVIRIS, these excluded bands included bands 1-6, 107-117, 153-170, and 217-224, leaving a total of 181 usable bands.

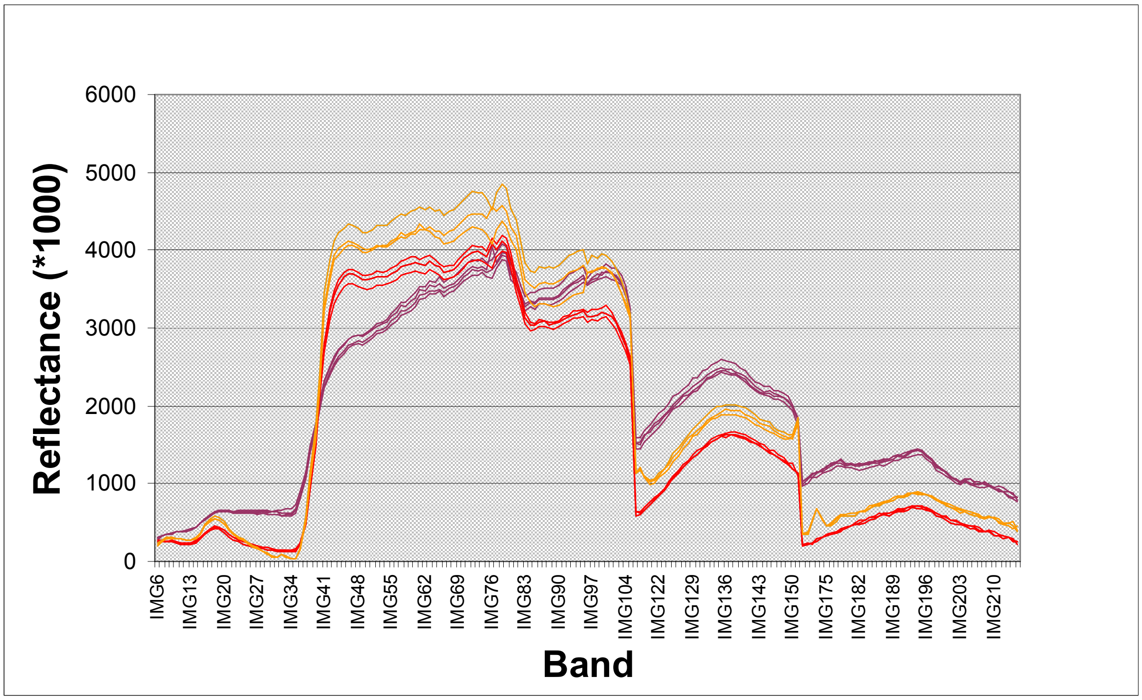

Figure 2.1. Example spectral response from AVIRIS hyperspectral sensor sampled at 3 plots (red, orange, and maroon), with 4 spectral “bundles” each. A spectral bundle is the spectral response recorded at the sample site and at 3 adjacent pixels to account for spatial registration errors. Statistical analysis of spectral response in relation to vegetation type was conducted using information from spectral bundles at sample sites.

The vegetation mapping models for each sensor employed the maximum number of field plots intersecting with each image individually for a total of 265 plots for the May AVIRIS mosaic, 233 plots for the July AVIRIS mosaic, and 299 plots for the multitemporal Landsat TM imagery. Both the AVIRIS and Landsat data covered the majority of the park and more than 98% of the vegetative inventory plots sampled for a total of 34 community types.

2.5.5 Topographic Gradients:

Maps of digital topographic gradients were produced for Shenandoah National Park to guide sample site selection, image processing, and vegetation distribution modeling. Table 2.4 lists the topographic variables included in statistical analysis and prediction of vegetation type. In addition to the topographic based variables listed, maps of geologic type (from Morgan et al 2004) and image specific illumination were also used as inputs to statistical analysis. Geologic types of alluvium, acidic sedimentary, granitic, mafic, and calcerous rocks were input as dummy variables into statistical models. In lieu of directly correcting for terrain related illumination effects in the imagery during preprocessing, "Cosine I" images were created to approximate the illumination angle of the sun that would be expected at the time of satellite image acquisition (Townsend and Foster 2002). Inclusion of this data as predictive variables in statistical analysis was meant to adjust for differential effects of solar illumination on vegetation spectral reflectance.

The topographic gradient layers were initially created from a 15 meter resolution digital elevation model (DEM) as described above. Topographic grids were resampled to 17 meter resolution using nearest neighbor resampling for equivalence with the AVIRIS hyperspectral data. Topographic gradients were additionally resampled to 30 meter resolution using nearest neighbor resampling for analysis with 30 meter Landsat TM data. Some topographic variables were filtered using a low pass 3-by-3 filter before resampling to minimize noise in the data analysis (e.g. planform curvature, profile curvature, relative moisture index, relative slope position, topographic convergence index, topographic relative moisture index, compound topographic index). Co-registered image and environmental gradient models were used as input to statistical classification models using specialized scripts written in IDL programming language for the ENVI image processing system, and for the SAS statistical language.

2.5.6 Image classification (Canonical Linear Discriminant Analysis):

Canonical discriminant analysis (CDA) is a multivariate statistical method that creates linear combinations of measured variables to optimize discrimination of samples into predetermined classes. Unlike more generalized data transformation and reduction techniques such as Principle Components Analysis (PCA) and Minimum Noise Fraction (MNF), CDA requires a training sample linked to predefined classes. When a training sample exists, CDA creates transformed canonical variates or components that maximize the discrimination between the classes of interest. Whereas PCA and MNF methods focus on capturing most of the image-wide data variability within the first few transformed dimensions, CDA focuses only on the data variability that is important to discriminating between classes, which can produce unique results. Figure 2.2 illustrates the loading of outcrop classes along two canonical variates constructed from image and topographic variables sampled at field plot locations, and demonstrates the discrimination between these classes.

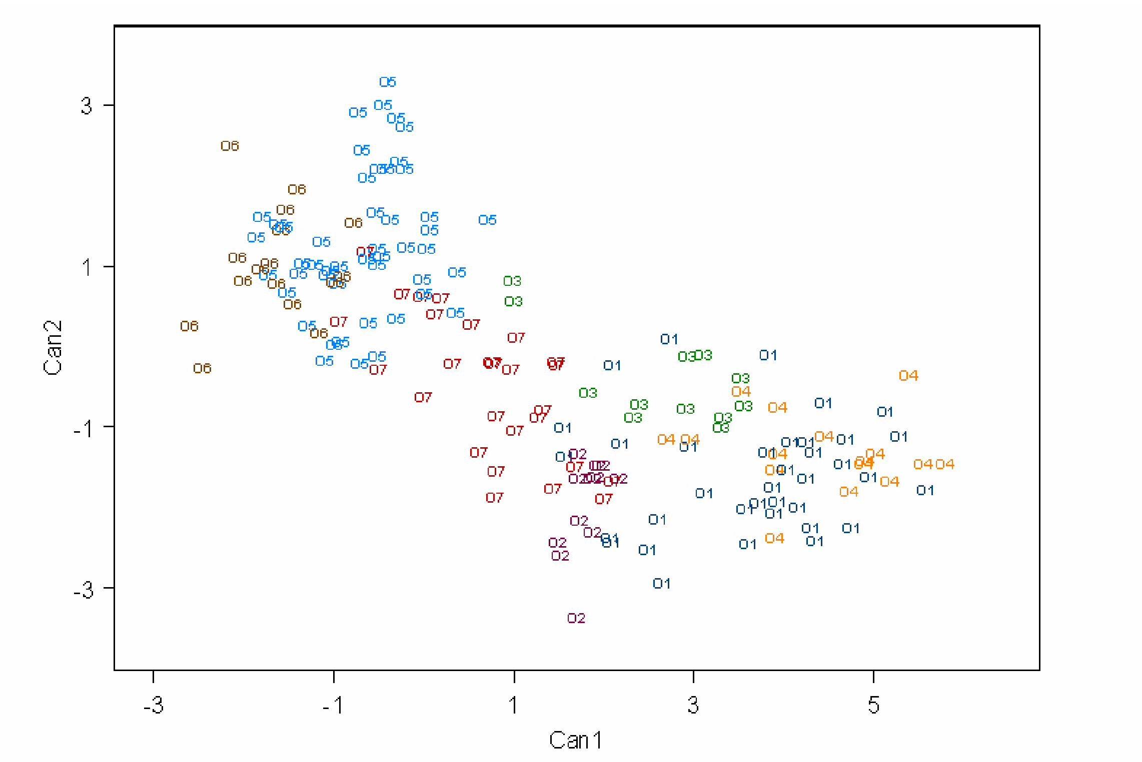

Figure 2.2. Illustration of loading of outcrop classes on two canonical axes constructed from image and topographic variables using Canonical Discriminant Analysis (CDA). Colors and text represent different classes of outcrop communities (e.g. O1, O2, etc.) and location of text labels represent relative loading of sample plots in relation to two canonical axes. Plots from the same vegetation community tend to cluster together, allowing prediction of vegetation class on the basis of image and topographic information.

Canonical Linear Discriminant Analysis (CLDA) employs linear discriminant analysis in conjunction with the canonical variates produced by the CDA to predict class membership. The first step in the CLDA analysis was to run stepwise discriminant analysis on all of the image and topographic variables (sampled from the training data) resulting in a subset of variables useful for discrimination between classes for each sensor. Table 2.9 lists the variables selected from each sensor and topographic variable set from CLDA analysis. Figures 2.3 and 2.4 illustrate the weighted importance of image and topographic variables used as input to CLDA. The CDA for this study was done using the CANDISC procedure in the SAS statistical software package. CANDISC produced one less canonical variate than the number of classes for a total of 22 canonical components. Once these were generated, PROC DISCRIM was used to create linear discriminant functions from combinations of the canonical variates. The linear discriminant functions were then mathematically transformed into probability values of class membership. The final models mapped the class with the highest membership probability at the training data locations.

Table 2.9. Image and topographic variables selected for use in canonical linear discriminant analysis models. *Landsat multi-temporal imagery from April 1984, September 1984, May 2000, May 2002, and September 2002.

AVIRIS May 2000		**AVIRIS July 2001**		**Landsat Multi-temporal***	
Variable	*Name*	*Variable*	*Name*	*Variable*	*Name*
IMGx	111 bands	IMGx	98 bands	IMGx	21 bands
TOPO0	Beers	TOPO0	Beers	TOPO0	Beers
TOPO1	Elevation	TOPO1	Elevation	TOPO1	Elevation
TOPO3	Plancurve	TOPO3	Plancurve	TOPO3	Plancurve
TOPO5	RMI	TOPO5	RMI	TOPO4	Procurve
TOPO6	RSP	TOPO6	RSP	TOPO5	RMI
TOPO7	Slope	TOPO7	Slope	TOPO6	RSP
TOPO8	Solar_ave	TOPO8	Solar_ave	TOPO7	Slope
TOPO9	TCI	TOPO9	TCI	TOPO8	Solar_ave
TOPO10	TRMI	TOPO10	TRMI	TOPO9	TCI
TOPO11	TSI	TOPO11	TSI	TOPO10	TRMI
TOPO13	COSI05	TOPO15	COSI07	TOPO11	TSI
TOPO19	Greenstone	TOPO16	CTI	TOPO12	COSI8404
TOPO20	Sandstone	TOPO19	Greenstone	TOPO13	COSI8409
TOPO21	Granite	TOPO21	Granite	TOPO14	COSI0205
TOPO22	Limestone	TOPO22	Limestone	TOPO16	CTI
				TOPO19	Greenstone
				TOPO20	Sandstone
				TOPO21	Granite
				TOPO22	Limestone

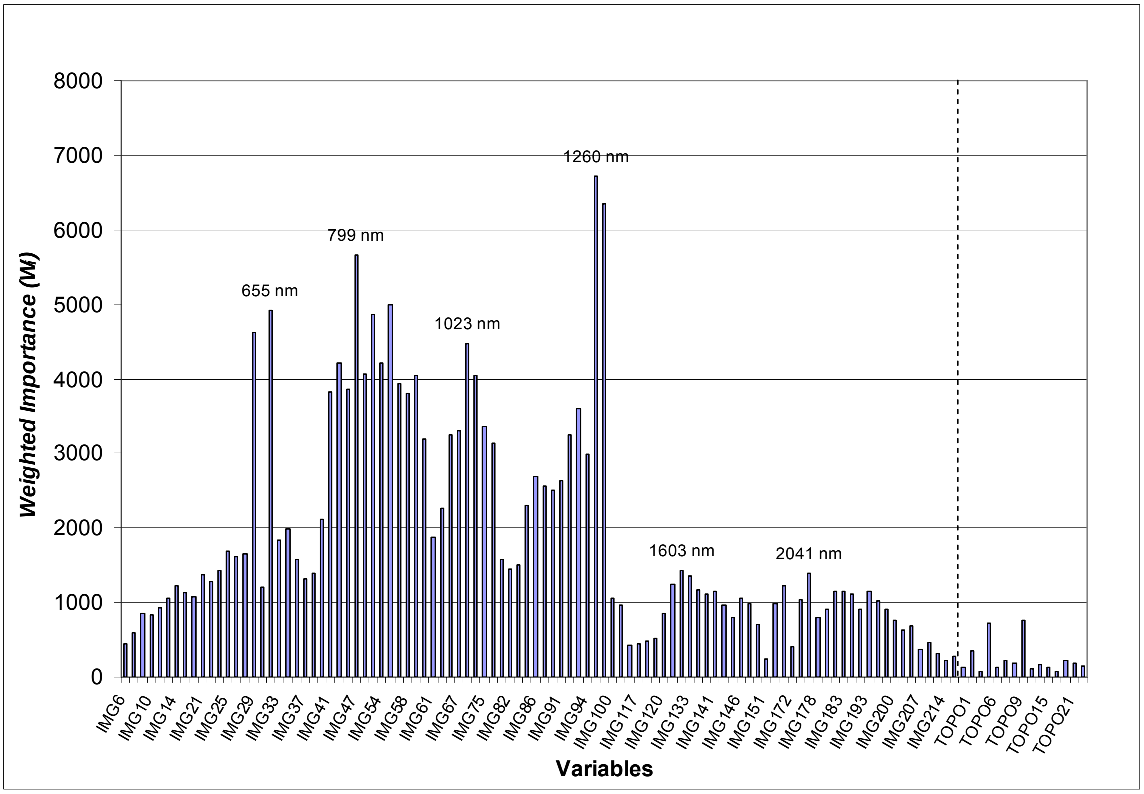

Figure 2.3. Weighted importance of variables used in July 2001 AVIRIS image model for discriminating between vegetation classes in CLDA analysis. Note the overwhelming importance of hyperspectral image variables compared to topographic variables (refer to Table 2.9 for explanation of variables).

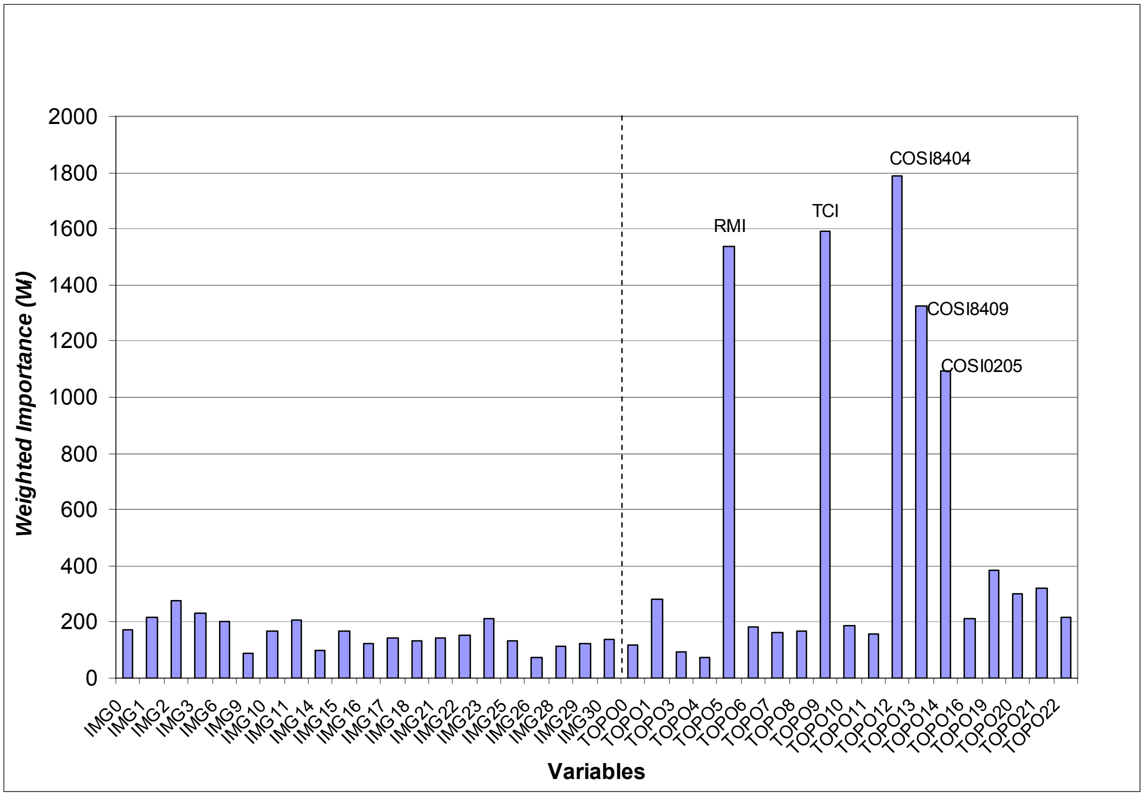

Figure 2.4. Weighted importance of variables used in multi-temporal Landsat image model for discriminating between vegetation classes in CLDA analysis. Note the importance of topographic variables compared to image variables (refer to Table 2.9 for explanation of variables).

Coefficients from the CDA and the linear discriminant functions were then applied to the combined image and topographic data to determine the most likely vegetation class at each pixel based on statistical functions. Results of this process are maps of predicted probabilities for each vegetation class. These probability maps are then combined and the maximum class probability at each pixel is determined and used to assign the vegetation type on the final map.

2.5.7 Post Classification Smoothing:

Statistical classification procedures used in our analysis (as well as other pixel-based processing) predict vegetation class based on statistical properties at individual pixels. Slight variations in properties between pixels (due to measurement precision variability, or random errors) can lead to adjacent pixels being assigned to different classes. The resulting map often has a “salt and pepper” speckled pattern from the intermingling of pixels of different classes. The goal of post-classification smoothing is to separate the “noise” pixels in this speckling pattern from the underlying vegetation community “signal” to form contiguous patches representing land cover classes on the ground. The typical process for smoothing out noise pixels is to use a majority filter operation to re-assign individual pixels to the class represented by a majority of surrounding pixels, or to eliminate individual pixels and replace them with surrounding pixels in a “sieve and clump” operation. However, these operations do not consider the information content of the pixels being eliminated, just their adjacency. Finding methods to consider both the information content and adjacency of pixels for intelligent post classification smoothing is an active area of research (see Qian, et al 2005). Due to the fact that maps of predicted probability for each class are produced with the CLDA classification method, it is possible to use this information to smooth out noise to produce contiguous patches, without losing information content.

We used GIS to compute the mean prediction probability within a 40-meter radius (~ 0.5 hectare) circular area around each pixel. This had the effect of generalizing the probabilities within a circular area equivalent to 0.5 hectares (the minimum mapping unit of the project). We generalized prediction probabilities in this manner for each of the 34 vegetation communities mapped. We combined the probabilities into a final generalized map by identifying the maximum predicted probability for each pixel on the filtered map, and assigning the class with the highest probability to the output map.

2.6 Accuracy Assessment

2.6.1 Generation of Random Sampling Points Stratified by Map Unit

We generated sample points for an accuracy assessment (AA) field survey using a draft vegetation map produced from AVIRIS hyperspectral imagery and topographic gradient models. We used a random point selection script in GIS to select areas from the draft map that were at least 50 m (164’) from a road (to minimize disturbance effects), but no more than 250 m (820.2’) from a road or trail (to minimize travel time). We excluded from AA point selection areas with canopy defoliation or disturbance occurring between 1984 and 2002 by assessing changes between leaf-on 1984 and 2002 Landsat Thematic Mapper satellite imagery (30 meter (84.2’) pixel resolution). We randomly selected AA survey locations for each vegetation community type within remaining park areas that were not in a disturbed or road influenced zone, but that were easily accessible by roads or trails. The numbers of points allocated to each community type were generated proportional to the area of the vegetation community within the park as determined from a draft map of vegetation polygons. For 2004, 280 points were selected for field assessment of which 224 points were visited representing 32 of 34 vegetation communities identified in the park.

For 2005, we generated additional accuracy assessment points in an attempt to sample underrepresented types from the 2004 AA field survey. We evaluated existing plot data (vegetation mapping plots, 2004 accuracy assessment plots, long-term ecological monitoring plots, plant protection plots) to find areas that were under-sampled, and we examined draft vegetation maps to find vegetation communities that were underrepresented. We buffered existing plot data to 200 meters and removed these areas from consideration for new plot selection to keep new AA plots away from previously sampled areas. We also examined plot representation of vegetation communities, and randomly placed plots in vegetation types that were under-represented on the basis of percent of park area covered by the community, and number of previous plots placed in that community. We targeted 199 random plots, and prioritized plots to insure that those community types least represented by prior field sampling would be visited first if all 199 plots could not be assessed in the field season. Of the 199 selected points, 68 were visited in the field in 2005.

2.6.2 Accuracy Assessment Field Sampling Protocol

Lists of random plot coordinates and maps showing locations of plots to visit were delivered to VANHP (2004) or SHEN (2005) for use by field personnel. A set of Accuracy Assessment (AA) protocols and a customized AA field data collection form (Appendix 4) consistent with the USGS-NPS Vegetation Mapping Program were developed in consultation with NatureServe. Subsequently, data were collected in the field by VANHP botanists and NPS biological technicians with no prior involvement with the project. The general procedure for this task was to navigate as closely as possible to the pre-selected point using a “wide area augmentation system” (WAAS)-enabled Garmin GPS unit. At the point, a new GPS waypoint was collected, a 0.5 ha (1.236 acre) circular plot (radius ~ 40 m, 131.2’) was established, and required environmental and floristic data were collected from the plot.

Using the field key to park vegetation types (Appendix 3) and draft descriptions, AA field crews identified the community type in each sample plot, and also recorded information about vegetation in a 0.5 ha (1.24 acre) around the AA location, to the extent that it was observed *en route* to and from the sample point. Sufficient data on vegetation structure, floristic composition, and environmental setting were recorded to evaluate the degree to which vegetation at sample sites was representative of a classified type. Where an exact match was not found between observed vegetation and the vegetation community described in the key, the closest matching types were recorded. For 2004 surveys, the degree of certainty the field crews had in the vegetation community type assignment was recorded on a numeric scale from 1-5. For 2005 surveys, the degree to which the observed vegetation matched the “archetype” of the community was recorded on a numeric scale from 1-5.

2.6.3. Accuracy Assessment of Map Data

Internal Accuracy Assessment of CLDA Models:

Predictive accuracy of the CLDA models from each sensor were evaluated using two separate metrics, resubstitution accuracy and cross validation accuracy. Resubstitution accuracy reflects how many of the plots are accurately placed in the correct class by the model. This is sometimes referred to as the percent plots correct or PPC and is indicative of the model's ability to accurately predict the training data set. Cross validation accuracy is a more conservative estimate calculated by creating the model *n* times, each time dropping out one of the *n* observations when building the model and using the dropped observations to validate the model. Cross validation is a more appropriate estimate of the model's ability to predict new data, though it is not as desirable as using an entirely separate dataset for validation. Because the final map product for SHEN was a merged version of results from different dates and sensors, the internal cross validation accuracies for the individual models could not be used to evaluate the final map

Incorporation of Field Sampling Data into Accuracy Assessment:

Field validation of the final vegetation mapping product is an integral part of National Vegetation Mapping Program efforts. Field validation plot data was incorporated into the accuracy assessment of the final map using a modified fuzzy evaluation approach. Fuzzy accuracy assessment methods help address the discrepancy between actual mixed forest composition that varies continuously over the landscape and "hard" classes that assign a pixel or polygon to a single discrete vegetation type. Fuzzy assessment generally acknowledges that for a given point on a classified map, when choosing among similar forest associations or classes, an on-the-ground observer may find two or three classes within the key that would acceptably characterize the site. This observation is understandable given the statistical clustering and ordination methods used to derive vegetation classes from the field plot data, as there will always be some overlap within the variance of each vegetation class. Within these overlapping regions, plots could be characterized as multiple types and still be considered accurately mapped.

This phenomena of multiple "right" answers for validation site class assignment had to be addressed when comparing the field validation data to the final map product for external accuracy assessment. The first issue that needed to be addressed was the change from a preliminary map used to locate field validation sites to the final map product. The preliminary map was the result of a different statistical technique (Classification Trees) that did not prove as effective as the CLDA modeling technique. Two issues in the validation data arose as a result of the change in methods and maps. The first was that the original proportion of map classes designed to be represented in the field validation sites was not necessarily maintained. The second issue was that validation plots that were placed within at least 0.5 ha (1.24 acre) polygons and away from polygon edges on the preliminary map often fell haphazardly along vegetation transitions or boundaries on the final map. This resulted in multiple map classes being represented by a majority of the ~0.5 ha (1.24 acre) field validation sites, which further required the use of fuzzy analysis in the accuracy assessment. The third major issue with the field validation data was that the field crew often recorded two and even three possible classes for a given validation site, perhaps recognizing the fact that multiple classes were acceptable or that the .5 ha (1.24 acre) area included multiple types. Their notes also indicated that sites with varying amounts of disturbance were more difficult to place within the classification scheme. This is expected as the original sampling was designed to avoid disturbed areas and instead focused on undisturbed forest types.

An accuracy assessment scheme was designed to account for a majority of the issues discussed above. In order to compare map classes to field validation observations, a 4x4 pixel analysis window (.46 ha, 1.14 acres) was placed around field validation sites to approximate the 0.5 ha (1.24 acre) area observed by field validation teams. All the classes occurring within each site window were extracted using GIS. Each window was then visually assessed and up to four possible correct classes were recorded. In most cases, the first two classes included the center pixel and majority class (most common class occurring in the window) if they were different. Additional possible classes were included when the window was evenly divided between 3 or 4 different types or when a type occurred in the window and was clearly very common just outside the window's extents. Using this methodology, 90% of the validation sites had at least 2 reasonable map classes within the analysis window. Only 23% of the sites had up to 4 possible correct classes. In comparison, 37% of the sites had at least 2 possible classes assigned to them in the field and 7% had 3 classes recorded in the field validation.

In an effort to increase sample size of accuracy assessment plots, collaborators at Virginia Natural Heritage (G. Fleming) examined vegetation composition at plots previously sampled in the park for the Long-term Ecological Monitoring (LTEM) program (1991-2001) and plant protection activities (2002-2004). A total of 277 plots were examined for vegetation composition. Of these plots, only 249 represented unique locations as more than one LTEM plot may have been recorded for each LTEM site. Plots were assigned geologic parent material type, elevation, aspect, slope, slope shape, topographic position, and landform codes to assist in assignment into vegetation community type. Each plot record was examined for vegetation composition and environmental attributes, and was assigned to the closest matching vegetation community type (e.g. map code) based on expert judgment. Where assignment to one type was not obvious, a second community type was listed. A "confidence level" of "confident" (80-100% certain), "probable" (50-80% certain), or "uncertain" (10-50% certain) was also assigned to each plot to denote how well the plot fit into the vegetation community class. Extenuating circumstances influencing the classification, such as disturbance or succession, were noted.

3. RESULTS

3.1 Landforms and Ecological Land Units

Ecological land unit mapping resulted in the creation of two new GIS layers: landforms and ecological land units (ELU) based on the 15 meter resolution digital elevation model. Other layers used as inputs to the ELU mapping effort (geology and elevation) were simply recoded from existing maps. Fourteen distinct landforms were mapped in the park. Most abundant landforms by area are sideslopes and steep slopes, but significant areas of cove and upper slope exist in the park as well (Figure 3.1). Landform types are illustrated in Figure 3.2.

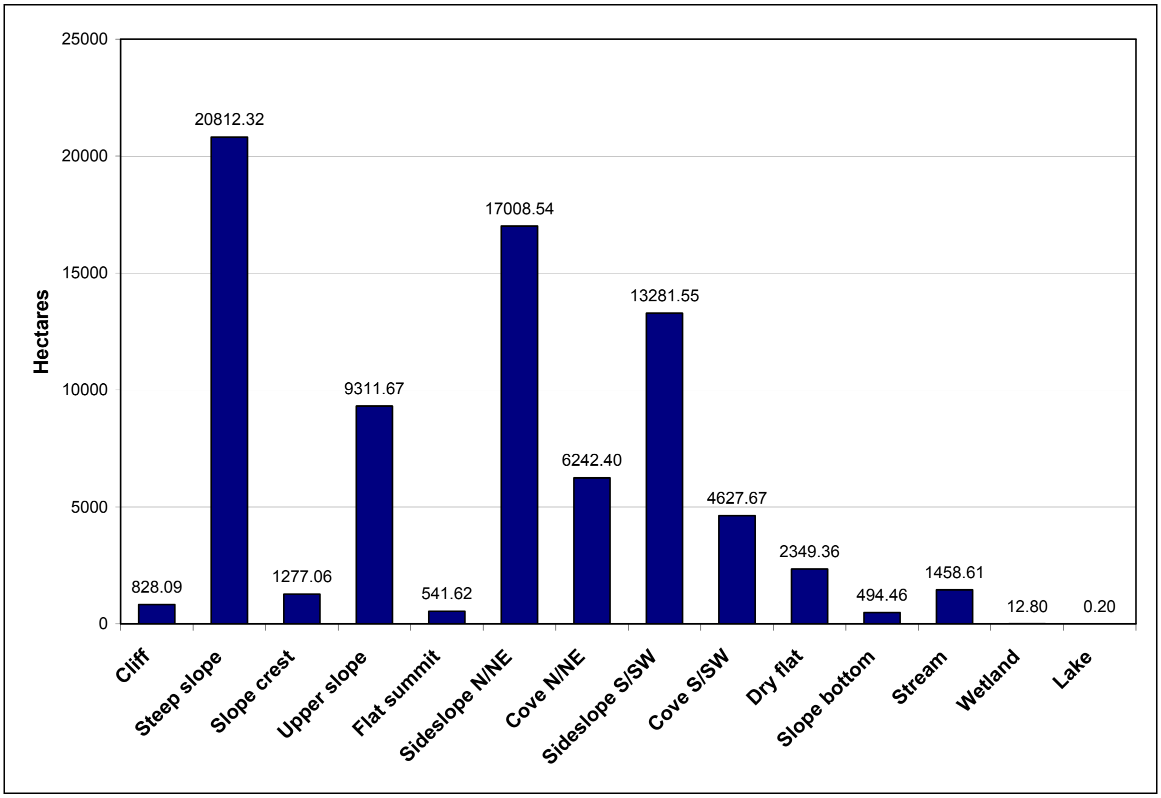

Figure 3.1. Landforms of Shenandoah National Park by area (ha).

Of the possible 210 combinations of elevation, geology, and landform types, 163 distinct ecological land units were mapped in the park. However, 40 ELUs represent less than 10 hectares each, and 15 of those comprise less than 1 hectare each. Twenty-eight ELU types represent over 1000 hectares, with the largest types being in mid elevation-basaltic-side slopes (8,583 ha), mid elevation-granitic-steep slopes (7,916 ha), mid elevation-siliciclastic-steep slopes (7,763 ha) and mid elevation-basaltic-N/NE facing side slopes (7,012 ha). Overall, the composition of ELU’s in the park is quite diverse, indicating the potential of numerous microhabitats available to plants.

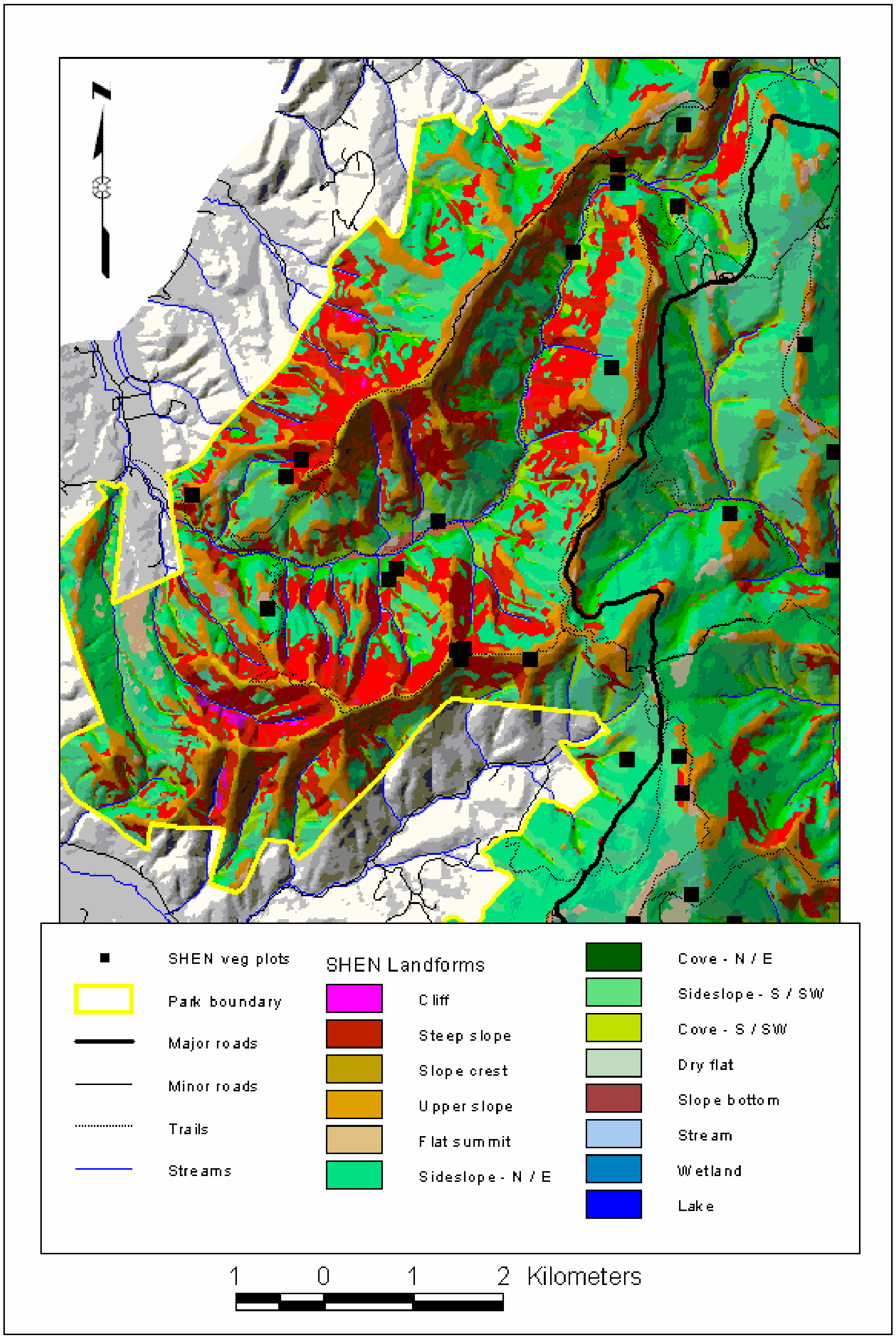

Figure 3.2. Example landform mapping results, Jeremy's Run area, North District, Shenandoah National Park

3.2 Vegetation and Accuracy Assessment Plots

As described in section 2.3, 311 total plots were sampled and used for classification in this project. Of the 311 total plots used for classification, 208 plots were sampled during the growing seasons of 2001, 2002, and 2003. Additionally, 93 plots were previously sampled using VANHP protocols during the period 1999-2001, and 10 additional plots were sampled prior to 1999. Figure 3.3a displays locations of sampled plots. Appendix 5 lists the plot coordinates of plots sampled and used for classification (n=305), as well as for plots dropped from statistical consideration as outliers (n=6). Figure 3.3b displays locations of 2004 AA plots. Figure 3.3c displays locations of 2005 AA plots.

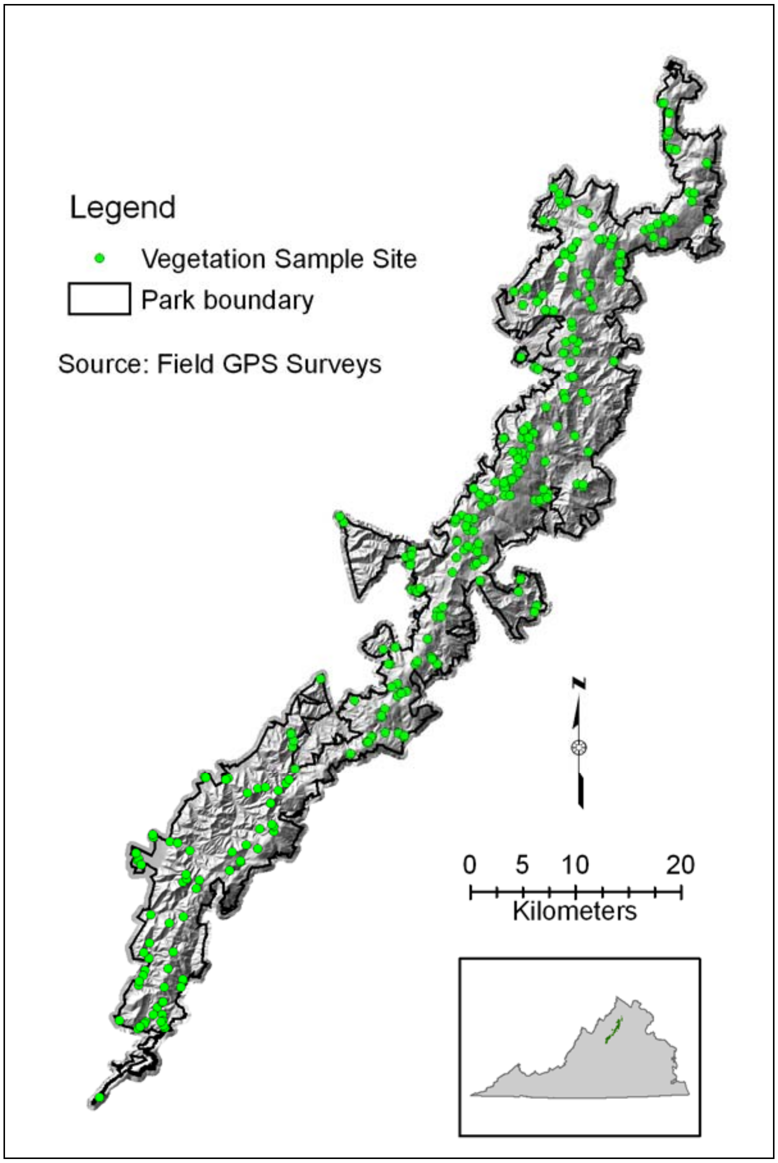

Figure 3.3a Location of vegetation field sampling plots (n=305) used for classification scheme development and as training sites for mapping, Shenandoah National Park.

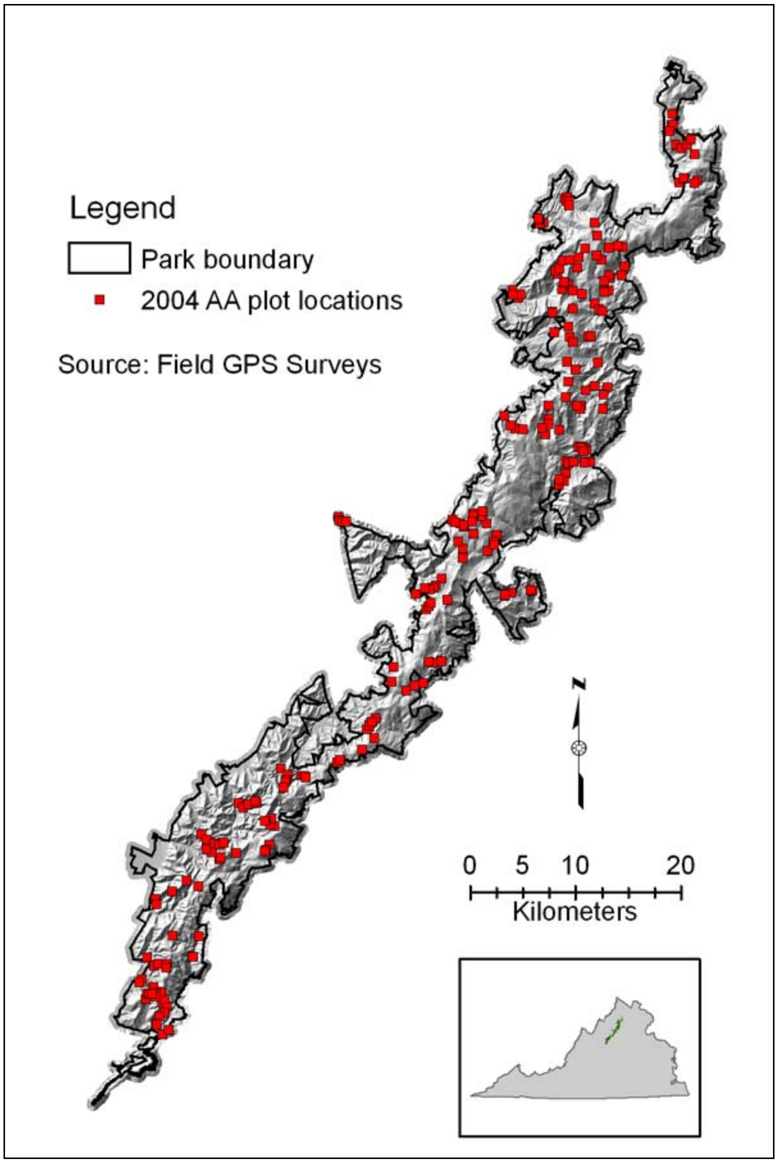

Figure 3.3b Location of accuracy assessment (AA) field sampling plots (n=224) collected in 2004, Shenandoah National Park.

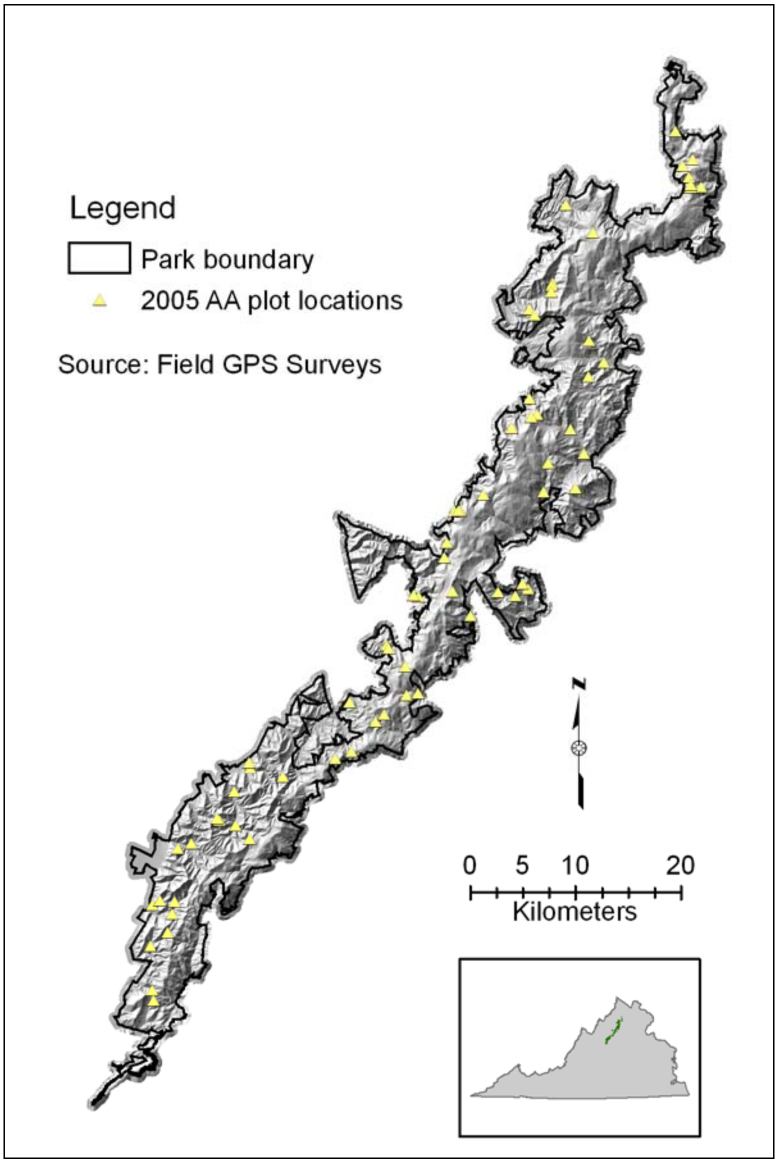

Figure 3.3c Location of accuracy assessment (AA) field sampling plots (n=68) collected in 2005, Shenandoah National Park.

3.3 Vegetation Classification Scheme

Based on the combined results of cluster analysis, summary statistical analysis, and ordination studies, 34 natural community types were recognized in the classification of Shenandoah National Park data. Three hundred and five (305) sampling sites and 762 vascular plant taxa were used in this classification. Six (6) sampling sites of the original 311 sites field sampled were dropped due to missing or incomplete data, or because they were outliers in the resulting classification and did not represent existing or unique vegetation associations. Membership in community types ranges from one to 31 plots. Thirty one (31) community types were assigned to existing USNVC units, while 3 new types were described and ranked.

The basic unit of classification is equivalent to the "association" recognized in traditional vegetation studies (Barbour, Burk, and Pitts 1987; Mueller-Dombois and Ellenberg 1974) and the U.S. National Vegetation Classification (USNVC; Grossman *et al.* 1998), representing stands of vegetation of relatively homogeneous composition that share a set of characteristic species and recur on the landscape under similar environmental conditions. Protocols of the USNVC were followed in naming the community types, using the scientific names of up to six characteristic species, with distinct vertical strata indicated. As a rule, species are listed by descending order of importance and structural position, *i.e.*, canopy species are listed first, followed by understory species, shrubs, and herbs. Nominal species in the same stratum are separated by a dash (-), while different strata are separated by a slash (/). Redundant varietal and subspecific epithets (*e.g*., *Quercus rubra* var. *rubra*) are not used in community names. The characteristic physiognomy (*i.e*., forest, woodland, shrubland, etc.) of a type is listed at the end of its name.

For convenience, community types are aggregated into the <u>ecological groups</u> and <u>ecological classes</u> of Fleming et al. (2006) representing natural groups of vegetation types sharing gross climatic, topographic, edaphic, physiognomic, and floristic similarities. The hierarchical arrangement of community types within the formal USNVC physiognomic-floristic hierarchy is presented in the index to Appendix 2.

Despite encompassing an inevitable degree of variation, the community types defined in this study are generally recognizable in the field and potentially mappable. However, because the classification is based on composition in all layers, not just the tallest, these community types differ considerably from "cover types" (*sensu* Eyre 1980) used in forestry and large-scale vegetation mapping. Since our purpose is to define ecological units, all plants at a site are considered. In forests, for instance, shrubs and herbs often respond to more subtle environmental gradients and may reveal more about local site conditions and associated animal species than do trees, which tend to be more broadly distributed and exhibit less environmental specificity. Likewise, herbaceous species occurring with low cover may be more restricted to certain site conditions and thus far more diagnostic of a community type than more widespread, dominant shrubs and trees. The species used as nominals may be characteristic of a type because of their abundance, constancy, or relative restriction to the type. Although they can never be surrogates for descriptions, the names of communities are constructed so that one can distinguish among types, identify types readily in the field, and assign new stands to previously classified types. In order to meet the first objective, an emphasis has been placed on diagnostic species (*e.g*., those with high adjusted IV values). However, in the prevailing mixed forests of this area and other regions in the eastern United States, characteristic canopy trees are usually not restricted to a particular type. Many forested types, despite having distinctive total floristic compositions, have variable overstories composed of wide-ranging tree species with low fidelity and indicator value. Exclusion of such species from a community name altogether is not desirable and obfuscates the ready identification of the type in the field. Hence the approach typically taken by VANHP ecologists in naming forest community types involves the combined use of indicator, constant, and dominant species, with nominal species of the tree strata often common to multiple types, and nominal species of the shrub and herb strata contributing more diagnostic value.

3.3.1 Hierarchical Classification of Ecological Groups and Associations:

The hierarchical classification and 34 natural communities of Shenandoah National Park are summarized in this section. Detailed descriptions of each community type are provided in Appendix 2.

I. HIGH-ELEVATION COMMUNITIES

1. Central Appalachian Northern Hardwood Forests

a. ***Betula alleghaniensis – Quercus rubra / Acer* (*pensylvanicum*, *spicatum*) / *Dryopteris intermedia – Oclemena acuminata* Forest**

Central Appalachian Northern Hardwood Forest (Yellow Birch – Northern Red Oak Type)

(USNVC CEGL008502, map code F7, 8 plots)

This association is limited to relatively small patches at the highest elevations (range 960 to 1225 m, 3150 to 4019 ft), particularly on rocky, west to north-facing slopes. Soils are extremely acidic with low base status and very high organic matter content. Dominant overstory trees are typically somewhat stunted and gnarled from repeated ice and wind damage. The type is somewhat transitional between high-elevation northern red oak forests (CEGL008506) and high-elevation boulderfield woodlands dominated by *Betula alleghaniensis* (CEGL008504), intergrading with both along topographic gradients.

2. Northern Red Oak Forests

a. ***Quercus rubra – Quercus alba / Ilex montana / Dennstaedtia punctilobula – Carex pensylvanica – Deschampsia flexuosa* Forest**

Northern Red Oak Forest (Pennsylvania Sedge – Wavy Hairgrass Type)

(USNVC CEGL008506, map code F9, 25 plots)

In the Park, this association is limited to gentle, mostly convex slopes and crests on the highest metabasalt and granitic ridges. It forms an extensive, almost continuous patch in the central district from the vicinity of Big Meadows N to the vicinity of The Pinnacle and Marys Rock. Smaller, outlying patches occur on Hightop, Stony Mt, The Sag, Mount Marshall, Hogback and other high-elevation ridges. Mean elevation of plots samples is 1060 m (3478’). Soils are extremely acidic and infertile, sometimes bouldery but usually with relatively low surface cover of rocks. The vegetation is typically an open, stunted forest dominated by somewhat gnarled *Quercus rubra* and containing moderately diverse understory and herbaceous layers.

3. High-Elevation Boulderfield Forests and Woodlands

a. ***Betula alleghaniensis / Sorbus americana – Acer spicatum / Polypodium appalachianum* Forest**
Central Appalachian High-Elevation Boulderfield Forest
(USNVC CEGL008504, map code O4, 4 plots)
This very distinctive association is restricted to high-elevation (mean = 1070 m, 3510'), mostly west to north-facing boulderfields of both metabasalt and granitic rubble. The physiognomy is mostly that of a woodland, and overstory trees are typically stunted and gnarled from frequent ice and wind damage. *Betula alleghaniensis* is the overwhelming canopy dominant, and community floristics are characterized by northern and high-elevation species. High cover of diverse lichens and bryophytes is also typical. Surface substrate averages 76% cover of loose boulders and stones; mineral soil could not be extracted from sampling sites. Large, outstanding examples occur on the north flanks of Hawksbill and Stony Man. This vegetation type intergrades with the Central Appalachian Northern Hardwood Forest (CEGL008502), which occupies adjacent sites with somewhat lower boulder cover and greater soil development.

4. High-Elevation Outcrop Barrens

a. ***Diervilla lonicera – Solidago simplex* var. *randii – Deschampsia flexuosa – Hylotelephium telephioides – Saxifraga michauxii* Herbaceous Vegetation**
High-Elevation Greenstone Barren
(USNVC CEGL008536, map code O1, 9 plots)
This community type represents high-elevation metabasalt outcrop barrens occurring at Franklin Cliffs, Hawksbill, Crescent Rock, Stony Man, and Mount Marshall. The vegetation occupies massive, wind- and ice-blasted metabasalt exposures on upper, west- to north-facing ridge flanks. Mean elevation of sampled stands is 1090 m (3576'), and exposed rock cover averages 67%. Soils (very limited) are extremely acidic and infertile. The vegetation is characterized by a patchwork of shrub thickets (typically < 25% cover in plot samples), herbaceous mats (typically < 40% cover), and crustose lichen colonies on exposed rock

surfaces. Northern and high-elevation species predominate and ten state-rare plant species are associated, including several long-range boreal disjuncts. This community type is endemic to six sites in Shenandoah National Park. There are probably less than 20 discrete outcrops supporting it, and the extreme rarity and small-patch size merits the assigned global rank of "G1."

b. ***Photinia melanocarpa – Gaylussacia baccata / Carex pensylvanica* Shrubland**
High-Elevation Outcrop Barren (Black Chokeberry Igneous/Metamorphic Type)
(USNVC CEGL008508, map code O3, 3 plots)
In the Park, this association occupies high-elevation metabasalt outcrops similar to those of the preceding. Habitats are more west-facing (vs northwest-facing), and have a lower mean elevation (975 m, 3199’). Soils (very sparse) are even less fertile than those of CEGL008536. The vegetation is characterized by shrub thickets (particularly of *Photinia melanocarpa* and/or *Gaylussacia baccata*), sparse herbaceous patches, and lichens. Although the known occurrences are on metabasalt, additional examples of this type could occur on granitic rocks in the Park. This shrubland occurs on outcrops of several plutonic and metavolcanic formations along the length of the Blue Ridge in VA. Most known examples are south of the Park, and some extend to elevations as low as 730 m (2395’).

c. ***Kalmia latifolia – Vaccinium pallidum* Shrubland**
High-Elevation Heath Barren / Pavement
(USNVC CEGL008538, map code O2, 3 plots)
Middle- to high-elevation cliffs and outcrops of granitic rocks at Old Rag and Millers Head support this shrubland in the Park. Additional occurrences may be present on other granitic outcrops, and possibly on some higher quartzite exposures. Exposed rock cover averages 52% and soil (extremely acidic and infertile) is limited. Total vegetation cover is typically < 25% in a plot sample and is characterized by dwarfed ericaceous shrub thickets with scattered, severely stunted *Pinus* spp. and *Quercus* spp.

II. LOW- TO MIDDLE-ELEVATION MESIC FORESTS

1. Rich Cove and Slope Forests

a. ***Liriodendron tulipifera* – *Aesculus flava* – (*Fraxinus americana*, *Tilia americana*) / *Actaea racemosa* – *Laportea canadensis* Forest**
Southern Appalachian Cove Forest (Typic Montane Type)
(USNVC CEGL007710, map code F10, 17 plots)
This is a lush mesophytic forest community of lower elevations on substrates weathered from metabasalt and pyroxene-bearing granites. Many or all sites supporting this vegetation were cleared or cut-over in the past. Elevation range of plot samples is 311 to 985 m (1020 to 3232 ft), mean of 629 m (2064 ft), with lower-slope topographic positions and easterly aspects prevalent. Slopes are concave in one or both directions and sites have relatively high moisture potential (TRMI). Soil samples are moderately acidic with moderately high Ca, Mg, Mn, and TBS levels. The herb layer of this association is very lush with patch-clonal forbs such as *Laportea canadensis* and *Caulophyllum thalictroides*. Species characteristic of higher elevations are mostly lacking from this type. The current vegetation is more or less the result of secondary succession; the abundance of understory *Acer saccharum* in some stands is probably an indicator of ongoing compositional changes (see CEGL006237 below). The assignment of this vegetation to the primarily southern CEGL007710 is a bit problematic, but it seems to fit fairly well, if a gradual shift in species composition and elevation is accepted. In the park, this community intergrades with nearly monospecific successional forests of *Liriodendron tulipifera* (CEGL007220, see below) along a seral gradient. It also may intergrade with the Park's other rich cove forest (CEGL006237), which typically occurs at higher mean elevation.

b. ***Acer saccharum* – *Fraxinus americana* – *Tilia americana* – *Liriodendron tulipifera* / *Actaea racemosa* Forest**
Central Appalachian Rich Cove Forest
(USNVC CEGL006237, map code F15, 5 plots)
Similar to the preceding but occurring at somewhat higher elevations. Sampled or documented in accuracy assessment primarily in coves of the central section of the Park (both flanks), and near Loft Mountain in the southern section. Occupies middle to upper-slope ravines and northerly slopes (often very bouldery) underlain by

metabasalt at ~640 to 1070 m (2100 to 3510 ft) elevation. Soils are extremely acidic, but have moderately high base cation levels. In the Park, this association is characterized by dominance or co-dominance of *Acer saccharum* and a suite of characteristic, nutrient-demanding mesophytic forbs, including *Aconitum reclinatum*, *Viola canadensis*, and *Angelica triquinata. Liriodendron tulipifera* is less characteristic of this type than the preceding, and is absent from higher-elevation stands. However, the type may intergrade with the Park's lower-elevation rich cove forest (CEGL007710) at intermediate elevations, or along a seral gradient.

2. Acidic Cove Forests

a. *Pinus strobus* – *Quercus* (*rubra*, *alba*) – *Liriodendron tulipifera* Forest

Central Appalachian Acidic Cove Forest (White Pine – Mixed Hardwoods Type)

(USNVC CEGL006304, map code F12, 7 plots)

This mixed hardwood-white pine forest community was documented from low-elevation coves on the western side of the Park. It occupies mesic lower slopes and flats at elevations < 600 m (1968'). Sites are underlain by metabasalt and charnockite but may have significant regolith of acidic colluvium from upslope Chilhowee group metasedimentary rocks. Soils are intermediate in base status. Expressions of this vegetation in the Park are typically well-developed, moderately diverse forests. *Pinus strobus* varies in abundance from widely scattered to dominant over small areas. Although not plot-sampled on the eastern flank of the Park, observations indicate that this type forms patches at the lower elevations on that flank as well.

3. Mesic Mixed Hardwood Forests

a. *Fagus grandifolia* – *Quercus* (*alba*, *rubra*) – *Liriodendron tulipifera* / *Polystichum acrostichoides* Forest

Mid-Atlantic Mesic Mixed Hardwood Forest

(USNVC CEGL006075, map code F6, 1 plot)

This distinctive forest community, dominated by *Fagus grandifolia*, was plot-sampled at a single site in a low-elevation ravine at the foot of the western slope bordering the Shenandoah Valley. Although bedrock is shale and limestone of the Waynesboro Formation, the surface regolith probably consists of acidic colluvium from upslope Chilhowee rocks. Soils are intermediate in base status. This stand appears to represent an outlier of vegetation that is characteristic and widespread on mesic uplands of the Piedmont Plateau to the east of the Park. Several additional patches of this vegetation have been observed or documented in accuracy assessment; most are in low-elevation hollows underlain by granitic rocks on the eastern periphery of the Park.

4. Eastern Hemlock-Hardwood Forests

a. ***Tsuga canadensis – Betula alleghaniensis* Lower New England / Northern Piedmont Forest**
Hemlock – Northern Hardwood Forest
(USNVC CEGL006109, map code F8, 7 plots)
This hemlock-hardwood forest occupies high-elevation ravines and, less frequently, cool sheltered sites at lower elevations. With one exception, plot-sampled sites are situated on gentle toe slopes and bottoms with abundant moisture; other examples in steep, rocky ravines are known in the Park but were not sampled. Elevation ranges from 378 to 995 m (1240 to 3264 ft), mean ~ 800 m (2625'). Surface substrate is often characterized by abundant boulder cover and soils are extremely acidic, but with moderately high Ca and Mg levels, probably reflecting the influence of materials weathered from Catoctin metabasalt or pyroxene-rich granites. Sites supporting this vegetation often have a mixed hydrology, *i.e.*, they are essentially "uplands" with small seep or stream inclusions. This type represents hemlock-northern hardwood vegetation with northern affinities. It co-occurs with the High-Elevation Seepage Swamp (CEGL008533) type, and may grade into it as site conditions become more generally saturated. Stands of this community are undergoing phyiognomic and compositional changes due to extensive, adelgid-related mortality of *Tsuga canadensis*.

5. Early-Successional Mesic Forests

a. ***Liriodendron tulipifera* / (*Cercis canadensis*) / (*Lindera benzoin*) Forest**
Successional Tuliptree Forest (Circumneutral Type)
(USNVC CEGL007220, map code F13, 4 plots)
This association represents nearly monospecific successional forests that grew up on fields abandoned in the

early 20th century. All sample plots occur on mesic, lower or middle slopes at < 450 m (1476') elevation, although the type was documented up to 823 m (2700') elevation during accuracy assessment. Underlying bedrock is metabasalt or pyroxene-rich granites and soils are relatively fertile. In cluster analysis, the plots forming this type were not separable from plots of the Montane Alluvial Forest (F11) and had to be segregated using other analytical methods. The environmental context of these two communities is distinctly different, although both share a diversity of weedy species and have similar histories of extensive anthropogenic disturbance. In the Park, this type appears to be a precursor of, and often transitional with, the lower-elevation rich cove type (CEGL007710) above, and is consistently characterized by almost monospecific overstory dominance by *Liriodendron tulipifera* and dense *Lindera benzoin* shrub layers. The sites supporting this type may have been disturbed more heavily or for a longer periods than those supporting rich cove forests.

b. ***Robinia pseudoacacia* Forest**
Black Locust Successional Forest
(USNVC CEGL007279, map code F21, 6 plots)
An early-successional forest community associated with abandoned fields and areas around old home sites. This type is scattered throughout the park but extends to higher topographic positions and higher elevations than does the ecologically similar *Liriodendron tulipifera* / (*Cercis canadensis*) / (*Lindera benzoin*) Forest (CEGL007220). Underlying bedrock is mostly metabasalt or granitic, and soils are intermediate in fertility. Although the six plots are basically from just two sites, similar vegetation has been observed or documented during accuracy assessment in many places in the Park, *e.g*., Milam Gap, Big Meadows, South River picnic area, Loft Mountain, etc. Current stands in the Park probably represent vegetation successionally transitional between pioneering forests once dominated by *Robinia pseudoacacia* and one or more of the montane or basic oak-hickory forests. This vegetation has a prominent component of invasive exotics such as *Alliaria petiolata* and often lacks *Liriodendron tulipifera*. It is treated here as part of the broad, USNVC *Robinia pseudoacacia* successional forest type.

III. LOW- TO MIDDLE-ELEVATION DRY AND DRY MESIC FORESTS AND WOODLANDS

1. Basic Oak-Hickory Forests

a. ***Quercus rubra – Quercus prinus – Carya ovalis / Cercis canadensis / Solidago caesia* Forest**
Central Appalachian Basic Oak-Hickory Forest (Submontane/Foothills Type)
(USNVC CEGL008514, map code F19, 7 plots)
In the Park, this forest community is primarily associated with low- to middle-elevation (< 815 m, < 2674') slopes underlain by metabasalt. Habitats are more mesic than those of other low-elevation oak-hickory forests (see CEGL006216 and CEGL008515 below). Sites are typically on rocky, middle and upper slopes with intermediate soil fertility. Southwesterly aspects prevail among plots, which may represent an artifact of limited sampling. This type is most common in the western Piedmont and is elevation-limited on the main Blue Ridge in Virginia. This community has a very diverse overstory with several *Carya* spp., *Quercus* spp., *Liriodendron tulipifera*, and *Fraxinus americana* prominent in variable proportions; it is almost impossible to name the type in a way that conveys this diversity. *Cercis canadensis* was very infrequent in plot samples from the Park, but was more common in AA points tagged to this type.

b. ***Quercus alba – Carya glabra – Fraxinus americana / Cercis canadensis / Muhlenbergia sobolifera – Elymus hystrix* Forest**
Northern Hardpan Basic Oak-Hickory Forest
(USNVC CEGL006216, map code F20, 3 plots)
In the Park, this association is known only from upper-slope benches on Dickey Ridge at elevations from 550 to 690 m (1804 to 2264 ft). Soils are shallow to bedrock and sites have substantial cover of loose boulders and stones, along with patches of exposed mineral soil. Soils extracted from plots have the highest mean pH, Ca, and Fertility Index (CEC x TBS/100) among classified types. This community type is endemic to the Piedmont and Blue Ridge foothills of northern Virginia and Maryland. It is most characteristic of diabase flatwoods of Culpeper Basin, where it is associated with mafic, hardpan soils. Examples also occur on slope benches of metabasalt foothills such as the Watery Mountains, where base-rich soils are shallow to bedrock.

Although known in the Park only from Dickey Ridge, it could also occur on low-elevation metabasalt slopes elsewhere. *Quercus prinus* is a common oak in the overstory mix in these Blue Ridge/foothill stands, but is absent from the distributional centrum on the Culpeper Basin.

2. Acidic Oak-Hickory Forests

a. ***Quercus alba – Quercus prinus – Carya glabra / Cornus florida / Vaccinium pallidum / Carex pensylvanica*** **Forest**
Central Appalachian Acidic Oak-Hickory Forest
(USNVC CEGL008515, map code F18, 5 plots)
This forest community is apparently restricted (or nearly so) in the Park to low-elevation slopes of the metasedimentary terrain on the Park's western flank. In most cases, geologic substrate is presumed to be metasiltstone or phyllite of the Harpers Formation. Strong compositional differences between this and the two oak/heath types cannot be explained by topography or soil chemistry, and are assumed to be related to soil texture, depth, and moisture-holding capacity. This vegetation probably occupies less fertile sites on the same shaley soils that support a more montane oak-hickory forest (see CEGL008516 below) at higher elevations. The Park represents the eastern margin of its distribution, which is centered in the shale districts of the Ridge and Valley province to the west.

3. Montane Mixed Oak and Oak-Hickory Forests

a. ***Quercus prinus – Quercus rubra / Hamamelis virginiana*** **Forest**
Central Appalachian Dry-Mesic Chestnut Oak – Northern Red Oak Forest
(USNVC CEGL006057, map code F5, 31 plots)
This association is one of the most extensive vegetation types in the Park, and is widespread at lower and middle elevations on all geological substrates. The elevation range of plot samples is 256 to 1018 m (840 to 3340 ft), mean of 564 m (1850’). It occupies various slope positions, as well as infertile, slope-base floodplains filled with bouldery quartzite alluvium. Sites are generally submesic and frequently very bouldery or stony. Soils have slightly higher base status than those of the area's oak / heath forests. Because it is compositionally variable and lies near the centrum of compositional and environmental gradients, this association is hard to characterize and has characteristics of

oak/heath, oak-hickory, and low-elevation boulderfield forests. It intergrades with many of the other major forest communities along topographic, moisture, and soil fertility gradients.

b. ***Quercus rubra – Quercus alba – Fraxinus americana - Carya* (*ovata*, *ovalis*) / *Actaea racemosa* Forest**
Central Appalachian Montane Oak-Hickory Forest (Basic Type)
(USNVC CEGL008518, map code F16, 18 plots)
This association comprises “rich" oak-hickory forests of middle to high-elevation ridge crests and gentle upper slopes, mostly over metabasaltic substrates (one plot each was located on charnockite and metasiltstone / phyllite). Elevation range of plot samples is 808 to 1067 m (2651 to 3501 ft), mean of 969 m (3179’). Based on AA data, the type also appears to occur locally in the 700-800 m elevation range, where it probably intergrades with the Central Appalachian Basic Oak-Hickory Forest (CEGL008514; see above). Soils are apparently deep, usually lack substantial rock cover, and are intermediate in fertility. This very distinctive type has an overstory of oaks, hickories, and white ash, along with a lush, forb-rich herb layer that resembles that of a rich cove forest. It covers fairly extensive areas in the Park and grades into Northern Red Oak Forests (F9) at higher elevations and into other oak and oak-hickory types at middle elevations.

c. ***Quercus prinus – Quercus rubra – Carya ovalis / Solidago* (*ulmifolia*, *arguta*) *– Galium latifolium* Forest**
Central Appalachian Montane Oak-Hickory Forest (Acidic Type)
(USNVC CEGL008516, map code F17, 12 plots)
This small- to medium-patch, rather dry but diverse oak-hickory forest occurs primarily on shaley units (metasiltstone, phyllite) of the Chilhowee Group at middle elevations in the southern section. It occurs most frequently on narrow, stony, convex crests and upper east-facing slopes. The elevation range of plot samples is 539 to 969 m (1768 to 3179 ft), mean of 800 m (2625’). Surface substrate is usually somewhat stony and contains locally large areas of exposed mineral soil. Soil samples had low to intermediate base status, except for high mean Mn. Overstory composition of this type is similar to CEGL008514 (in Basic Oak-Hickory Forests group) but the herbaceous vegetation

is very different and reflects the drier, more montane habitats.

4. Oak / Heath Forests

a. ***Quercus prinus* – (*Quercus coccinea*, *Quercus velutina*) / *Kalmia latifolia* / *Vaccinium pallidum* Forest**
Central Appalachian / Northern Piedmont Low-Elevation Chestnut Oak Forest
(USNVC CEGL006299, map code F3, 22 plots)
This association occurs on dry, rocky, infertile slopes at lower to middle elevations throughout the Park, but is particularly extensive on the dry, acidic metasedimentary substrates of the western Blue Ridge flank in the south district. Soils collected from plots are extremely acidic and infertile, with high Fe levels. This is the Park's characteristic dry-site forest dominated by *Quercus prinus* and typically an evergreen shrub layer of *Kalmia latifolia*.

b. ***Quercus coccinea* – *Quercus velutina* – *Quercus alba* / *Amelanchier arborea* / *Gaylussacia baccata* Forest**
Mixed Oak / Heath Forest (Low-Elevation White Oak – Scarlet Oak – Black Oak Type)
(USNVC CEGL008521, map code F4, 10 plots)
This association forms the principal forest cover on the low-elevation alluvial fan terrain at the western foot of the Park, mostly in the south district. The co-dominance of *Quercus alba* with other *Quercus* spp. is distinctive among the two oak/heath types in the Park, and the shrub layer is typically dominated by *Gaylussacia baccata* and other deciduous ericads. Sites are gentle (0 to 10-degree slope) lower slopes and flats at very low elevations (< 500 m, < 1640') at the foot of the western Blue Ridge flank. Underlying bedrock (principally shale and limestone of the Waynesboro Formation) is well covered by deep colluvial and alluvial fan deposits weathered from upslope Chilhowee Group quartzite. Soil chemistry is similar to the preceding type. This community type is most abundant on similar, rolling terrain of the Piedmont Plateau east of the mountains.

5. Pine-Oak / Heath Woodlands

a. ***Pinus* (*pungens*, *rigida*) / *Quercus ilicifolia* / *Gaylussacia baccata* Woodland**
Central Appalachian Pine – Oak / Heath Woodland

(USNVC CEGL004996, map code F1, 8 plots)
This association covers large areas on the metasedimentary substrates in the southern section of the Park, but is much less common on the granitic suite and metabasalt elsewhere. Stands typically occur on south- to west-facing, convex, upper slopes, ridge crests, and cliff-tops. These sites are among the most xeric and infertile habitats in the Park, and most have a demonstrable history of fires. The most characteristic physiognomic expression is an open woodland of stunted *Quercus prinus*, *Pinus rigida*, and/or *Pinus pungens*, with dense shrub thickets of *Quercus ilicifolia* and ericads. To a great extent, the dominant pines of this vegetation require occasional burning for regeneration, and some stands from which fire has been absent for long periods have become nearly closed forests. Because of recent depredations by the southern pine beetle, existing plot samples from the Park have rather low pine cover, even though they clearly represent the type.

6. Mountain / Piedmont Basic Woodlands

a. ***Fraxinus americana – Carya glabra / Muhlenbergia sobolifera – Helianthus divaricatus – Solidago ulmifolia* Woodland**
Central Appalachian Basic Woodland
(USNVC CEGL003683, map code O5, 14 plots)
This low-elevation (475 to 750 m, 1558 to 2461 ft) dry woodland occurs on metabasalt and other base-rich substrates of the Central Appalachians, but is known only from metabasalt in the Park. It is typical of rocky, south- to west-facing slopes, forming a woodland "matrix" around exposed cliffs and outcrops. Bedrock and boulder cover in plot samples averages > 40%. Levels of pH, Ca, Mg, and TBS in soil samples from plots are among the highest in the Park. Open, stunted overstories tend to be dominated by *Fraxinus americana* and *Carya* spp.; a diversity of dry-mesophytic and xerophytic shrubs and herbs is associated.

7. Low-Elevation Boulderfield Forests and Woodlands

a. ***Quercus prinus – Betula lenta / Parthenocissus quinquefolia* Talus Woodland**
Chestnut Oak – Black Birch Wooded Talus Slope
(USNVC CEGL006565, map code F2, 7 plots)
This community is widespread in the Park on boulderfields and bouldery colluvial slopes weathered from resistant

quartzites of the Chilhowee Group in the southern section. Scattered occurrences occupy similar habitats on granitic terrain and, rarely, metabasalt. This association ranges from the lowest elevations to ~ 975 m (3200'). Northerly slopes prevail among plot samples, but this is probably an artifact of limited sampling. Soils could not be extracted from all plots; those that could were extremely acidic and infertile, with high Fe levels. These habitats are extremely difficult to plot-sample, which is why the type is under-sampled in the Park. Physiognomy is quite variable, ranging from very open woodlands of gnarled *Betula lenta* to more closed stands of mixed *Betula* and *Quercus prinus*. *Betula lenta* is generally a pioneer woody invader of open boulderfield edges. As boulderfields weather and soil material fills the intersticial spaces, oaks and other species become established. This type grades into other forest communities (particularly the chestnut oak - red oak forest [CEGL006057]) along topographic gradients.

b. ***Tilia americana – Fraxinus americana / Acer pensylvanicum – Ostrya virginiana / Parthenocissus quinquefolia – Impatiens pallida* Woodland**
Central Appalachian Basic Boulderfield Forest (Montane Basswood – White Ash Type)
(USNVC CEGL008528, map code F14, 14 plots)
This association is widespread in the Park on boulderfields and bouldery colluvial slopes weathered from Catoctin metabasalt and, less frequently, pyroxene-bearing granitic rocks. It usually occupies steep middle slopes and is especially extensive in the elevation zone from 762 to 914 m (2500 to 3000 ft), less commonly extending to 500 m (1640') and 1040 m (3412'). Boulder cover in plot samples averages > 50% and soils have moderately high Ca and Mg. Distribution of this type is centered in the elevation zone where *Liriodendron tulipifera* drops out as a dominant tree of coves and mesic slopes. Because of constraints imposed by the Alliance level of the USNVC, this type is formally classified (in the USNVC) as a woodland, but is better characterized as an open forest. *Tilia americana*, *Fraxinus americana*, and *Quercus rubra* are the usual overstory dominants in varying proportions; shrub and herb-layer densities, as well as overall species-richness, vary considerably with the relative abundances of rock cover and intersticial soil material.

8. Early Successional Dry and Dry-Mesic Forests

a. ***Pinus virginiana* Successional Forest**
Virginia Pine Succesional Forest
(USNVC CEGL002591, *[not mapped], 0 plots)
This association occurs very locally in the Park at lower and middle elevations. It is a pioneering forest on dry, eroded, and/or depleted soils of old fields and pastures Most of these areas are underlain by the more base-rich metabasaltic and granitic rocks, and are located both on broad crests and relatively gentle side slopes. This type accommodates both monospecific stands of *Pinus virginiana* and decadent stands in which *P. virginiana* is co-dominant with emergent hardwoods. Various *Quercus* spp., *Carya* spp., *Liriodendron tulipifera*, and *Acer rubrum* appear to be the most frequent tree associates; understory and herbaceous species vary widely with site conditions and land-use history. This community type was not plot-sampled, but was documented in several locations by observations and accuracy assessment procedures.

IV. LOW- TO MIDDLE-ELEVATION ROCK OUTCROPS AND BARRENS

1. Low-Elevation Basic Outcrop Barrens

a. ***Juniperus virginiana – Fraxinus americana / Carex pensylvanica – Cheilanthes lanosa* Wooded Herbaceous Vegetation**
Central Appalachian Circumneutral Barren
(USNVC CEGL006037, map code O6, 8 plots)
This community type comprises low-elevation (< 580 m, < 1903’) outcrop barrens on Catoctin metabasalt and is documented in the Park from Dickey Ridge, lower Overall Run, Cedar Run, and Goat Ridge. Sites are typically on steep (~27 degree) middle slopes with south or west aspects. Surface cover of bedrock and loose rocks in plots averages > 60%. Mean pH, Ca, Mg, and TBS levels in soil samples were among the highest of classified vegetation types in the Park. Stands usually occur in small patches and have dense patches of graminoids (*e.g.*, *Schizachyrium scoparium*, *Carex pensylvanica*, *Bouteloua curtipendula*) and xerophytic forbs; widely scattered, stunted trees and shrubs are intermingled. Although confined to metabasalt in the Park, this association also occupies sites underlain by

calcareous shales and sandstones in the adjacent Ridge and Valley province.

b. ***Fraxinus americana / Physocarpus opulifolius / Carex pensylvanica – Allium cernuum –*** **(*Phacelia dubia*) Wooded Herbaceous Vegetation**
Central Appalachian Mafic Barren (Ninebark / Pennsylvania Sedge Type)
(USNVC CEGL008529, map code O7, 7 plots)
This is the "middle-elevation" (~550 to 1036 m, 1804 to 3400 ft) rock outcrop barren of metabasalt and pyroxene-bearing granites in SHNP. Most sites are on steep (mean = 30-degree), westerly, middle to upper-slope, convex outcrops. Surface cover of bedrock and loose rocks in plots averages > 60%. Soil samples have intermediate base status. Physiognomy of stands is similar to the preceding type. Compositionally, this association lacks many typical low-elevation species present in CEGL006037 and contains a number of distinctly montane species.

V. ALLUVIAL FLOODPLAIN COMMUNITIES

1. Piedmont / Low Mountain Alluvial Forests

a. ***Liriodendron tulipifera – Platanus occidentalis – Betula lenta / Lindera benzoin / Circaea lutetiana*** **ssp.** ***canadensis*** **Forest**
Northern Blue Ridge Montane Alluvial Forest
(USNVC CEGL006255, map code F11, 13 plots)
This forest community is apparently confined to the larger, mountain-foot floodplains with relatively fertile alluvial deposits. Habitats are nearly flat, bouldery, and well-drained, with moderately fertile soils derived from metabasalt, pyroxene-rich granites, or metasiltstone/phyllite. Many of these sites were probably cleared and subjected to multiple disturbances during the historical period in which the Park area was heavily populated. This type does not occur on sterile, acidic alluvium derived from the Chilhowee Group and deposited in floodplains at the foot of the western flank. CEGL006255 is a new USNVC type based on plot data from the Park and other qualitative data.

IV. NON-ALLUVIAL WETLANDS

1. Mafic Fens and Seeps

a. ***Spiraea alba* var. *latifolia* – *Cornus racemosa* / *Calamagrostis canadensis* – *Sanguisorba canadensis* – *Carex scoparia* Shrub Herbaceous Vegetation**
Northern Blue Ridge Mafic Fen
(USNVC CEGL006249, map code W1, 4 plots)
This community appears to be endemic to Shenandoah National Park, where it is confined to groundwater-saturated, high-elevation stream-head wetlands in the vicinity of Big Meadows on both sides of Skyline Drive. All stands have been disturbed by hydrologic alterations, excessive deer grazing, and probably fire exclusion. It is similar to another shrubland of mafic seeps in the southern Blue Ridge of VA and NC. CEGL006249 is a new USNVC type defined to cover this vegetation. It is a demonstrably rare vegetation type of considerable conservation concern.

2. Woodland Seeps

a. ***Caltha palustris* – *Impatiens capensis* – *Viola cucullata* Herbaceous Vegetation [Provisional]**
Central Appalachian Woodland Seep
(USNVC CEGL006258, map code W3, 2 plots) This provisional vegetation type is represented by two plot samples located in narrow, groundwater-saturated seeps that are closely bordered by upland vegetation. The two samples are quite different and do not form a strongly homogeneous group. Similar habitats and vegetation are scattered throughout the Park. CEGL006258 is a new USNVC type defined to cover this vegetation. More inventory and data collection in the Central Appalachians is needed to make this classification unit more robust. Similar communities from the southern Blue Ridge have been classified. At least one of the occurrences in the Park is much smaller than the minimum mapping unit size (0.5 ha)

3. Mountain / Piedmont Acidic Seepage Swamps

a. ***Acer rubrum* – *Nyssa sylvatica* / *Ilex verticillata* – *Vaccinium fuscatum* / *Osmunda cinnamomea* Forest**
Central Appalachian Acidic Seepage Swamp
(USNVC CEGL007853, map code W2, 3 plots)

This saturated forest community occurs along headwaters streams on the acidic, metasedimentary terrain of the western flank. All known examples are at very low elevations (< 500 m, < 1640') on ancient alluvial fans bordering the Shenandoah Valley. Habitats typically feature braided streams with *Sphagnum*-covered hummocks. Soils are extremely acidic and infertile, with high Fe levels. The few known stands in the Park conform closely to the USNVC description, although plot SHNP632 is a marginal, somewhat disturbed example.

4. Mountain / Piedmont Basic Seepage Swamps

a. *Acer rubrum – Fraxinus americana – Fraxinus nigra – Liriodendron tulipifera / Carex bromoides – Caltha palustris* Forest

Central Appalachian Basic Seepage Swamp
(USNVC CEGL008416, map code W4, 8 plots)
Lower- to middle-elevation forests occurring in linear patches along groundwater-saturated bottoms of streams and in headwaters seepage areas. Plot-sampled sites range from 421 to 939 m (1381 to 3081 ft) elevation, mean of 832 m (2730'), and are confined to substrates weathered from metabasalt and base-rich granites. Habitats are generally very bouldery and gravelly, with pronounced hummock-and-hollow microtopography and braided streams. Soils collected from plots have relatively high pH, Ca, Mg, Fe, and TBS levels. This type clearly represents a basic forested seepage wetland type conceptually similar to CEGL008416, but exhibits compositional variation related to topography (particularly increased importance of *Betula alleghaniensis* and *Tsuga canadensis* as elevation increases). At middle elevations, it grades into the High-Elevation Seepage Swamp type (CEGL008533) below, and several plots could be assigned almost equally well to either type. *Fraxinus nigra*, which is considered "diagnostic" of these wetlands, reaches its southern limits in VA and is quite sporadic in the Park (it is present in only half of the plots). Similar topographic gradation, as well as gradation apparently related to soil chemistry, has been noted on a regional level.

5. High-Elevation Seepage Swamps

a. ***Tsuga canadensis – Betula alleghaniensis / Veratrum viride – Carex scabrata – Oclemena acuminata* Forest**
High-Elevation Hemlock – Yellow Birch Seepage Swamp
(USNVC CEGL008533, map code W5, 8 plots)
Middle- to high-elevation forests occurring in linear patches along groundwater-saturated bottoms of streams and in headwaters seepage areas. Plot-sampled sites range from 670 to 1036 m (2198 to 3400 ft) elevation (most are > 900 m, > 2953’) and occur on all major substrate types. Habitats are generally less rocky than those of the Mountain / Piedmont basic seepage swamp (CEGL008416) above, but have similar hummock-and-hollow microtopography and braided streams. Soils have low to intermediate base status. Stands of this community are undergoing physiognomic and compositional changes due to extensive, adelgid-related mortality of *Tsuga canadensis*.

6. Shenandoah Valley Sinkhole Ponds

a. ***Quercus palustris / Panicum rigidulum* var. *rigidulum – Panicum verrucosum – Eleocharis acicularis* Herbaceous Vegetation**
Shenandoah Valley Sinkhole Pond (Typic Type)
(USNVC CEGL007858, map code W6, 1 plot)
The Park boundary runs through a single small but representative example of a Shenandoah Valley sinkhole pond. The habitat is seasonally flooded, with aluminum-rich clay soils. Many stands of this community type occur just outside the western Park boundary in Augusta, Rockingham, and Page Counties. They occupy seasonal ponds developed on the massive alluvial fans deposited along the base of the Blue Ridge over former karst terrain. This association is endemic to a three-county area of the Shenandoah Valley in Virginia.

3.3.2 Relationship of Vegetation to Field-Measured Environmental Variables:

The relationship between compositional groups and environmental gradients was examined in a series of NMDS ordinations (Appendix 1). Important topographic / hydrologic and soil chemistry gradients are identified by joint plot vector overlays on each ordination diagram. Each environmental factor with a Pearson product-moment correlation of r >|0.45| with stand scores on any of the axes is plotted as a vector, the direction of which indicated the direction of maximum correlation through ordination space. Vector line lengths are determined by the strength of the correlation. This critical value for the correlation coefficient is provided in the caption for each ordination diagram. Significance levels are uncorrected for multiple comparisons. Joint plots differ from biplots in that vectors emanate from the centroid of ordination space rather than the origin of the axes, and vectors are based on correlations instead of least-squares regression equations (McCune and Mefford 1999). Because vectors in PC-ORD joint plots are not scaled, the strengths of environmental gradients are not comparable between ordination diagrams.

When stand distributions in the various ordination diagrams are examined, the disposition of major vegetation groups and community types generally corresponds well with clusters identified by the Lance-Williams flexible beta method. As a whole, the ordinations indicate that bedrock parent material, soil fertility, elevation, and topographic position are the most important, interrelated environmental factors influencing major vegetation patterns in Shenandoah National Park. TRMI (site moisture potential), slope shape, slope inclination, Beer's-transformed aspect, and surface substrate characteristics are less important correlates of major vegetation patterns, although they frequently characterize differences between community types within the major groups (Appendix 2).

The results of these ordination studies suggest that bedrock stratigraphy in Shenandoah National Park exerts strong topographic control that results in more or less regularly recurring landforms, as well as somewhat predictable variation in site moisture and soil chemistry.

3.3.3 Summary of Riparian and Wetland Zone Vegetation:

Riparian and wetland vegetation is very limited in Shenandoah National Park, covering approximately 1632 hectares (4,032 acres), or 2% of the park. Vegetation generally falls into three hydrologic classes of Cowardin *et.al* (1979): temporarily flooded forests, saturated forests and shrublands, and seasonally flooded herbaceous vegetation.

Narrow but definite alluvial floodplains along larger streams at the lowest elevations support both palustrine and terrestrial forests. Hydrologic regime is probably similar to that reported for Passage and Mill Creeks in the Massanutten

Mountains (Shenandoah County), where small-scale alluvial landforms greatly influence species distributions (Hupp 1982, Hupp 1986, Olson and Hupp 1986). The lowest terraces of these narrow bottoms are probably flooded briefly once a year, while higher terraces are inundated only during rare, catastrophic floods. Microtopography is complex and usually includes multiple floodplain terraces, fans at tributary hollow mouths, various bank features, bouldery and cobbly depositional bars, and coarse woody debris transported by floods. Soils are highly variable, lack profile development, and range from well-drained to poorly drained. Along larger streams that drain large areas of granitic and greenstone terrain, soil fertility is typically high and at least some obligate wetland species are present. The Northern Blue Ridge Montane Alluvial Forest (map unit F11) is the principal community type on these more fertile, moisture-holding floodplains, which are most extensive at the foot of the eastern slope, and the foot of the western slope in the North District.

Similar floodplains on the western flank of the park that drain large areas of Chilhowee Group metasedimentary terrain have extremely acidic, nutrient-poor soils that appear to be much more drought-prone despite their low topographic position. These sites typically support variants of upland forests in the park, principally the Central Appalachian Dry-Mesic Chestnut Oak – Northern Red Oak Forest (map unit F5) or the Central Appalachian Acidic Cove Forest (White Pine – Mixed Hardwoods Type; map unit F12), and obligate wetland species are lacking.

The park has a great diversity of seepage wetland vegetation that also exhibits a strong correlation with substrate conditions. Narrow spring runs, mostly shaded by trees rooted in adjacent upland forests, are scattered throughout the park on granitic and metabasaltic substrates, supporting the herbaceous Central Appalachian Woodland Seep community type. Along larger headwaters streams where spring runs coalesce in larger, braided bottoms or where lateral groundwater seepage is abundant, forested wetlands are characteristic. Three associations, separated by soil preferences and elevation, are present in the Park: the Central Appalachian Acidic Seepage Swamp (map unit W3) on low-elevation metasedimentary substrates; the Central Appalachian Basic Seepage Swamp (map unit W4) on low- to middle-elevation granitic and metabasaltic substrates; and the High-Elevation Hemlock-Yellow Birch Seepage Swamp (map unit W5) at elevations mostly above 900 m (occasionally lower in sheltered habitats).

The most noteworthy seepage wetland is the Northern Blue Ridge Mafic Fen (map unit W1), which appears to be endemic to high elevations of the Central District near Big Meadows. Physiognomically, this vegetation type is a mosaic of shrubs and herbaceous openings, and several state-rare plant species are characteristic. The type is strongly affiliated with unconsolidated soils, washed from Catoctin metabasalt, that are highly acidic and rather low in base status excepting high Mg, Fe, and Al. Complete descriptions of each wetland community type are provided in Appendix 2.

3.3.4 Relationship of Vegetation to Ecological Land Units

Plots sampled fell in 83 different ecological land units as defined by GIS and described in sections 2.1.1 and 3.1. Of the 305 field sampling plots used in classification, 111 (36%) were placed in just 8 ELU types; mid elevation-basaltic-steep slopes (n=29), mid elevation-basaltic-S/SW facing side slopes (n=16), high elevation-basaltic- upper slopes (n=14), high elevation-basaltic-S/SW facing side slopes (n=11), mid elevation-siliciclastic-steep slopes (n=11), high elevation-basaltic-flats (n=10), high elevation-basaltic-N/NE facing side slopes (n=10), and low elevation-basaltic-N/NE facing side slopes (n=10). By contrast, 194 (64%) of field plots were placed in the remaining 75 ecological land units. A total of 20 field plots were placed in riparian or wetland ELU types (e.g. stream side, slope bottom, or wetland landform types). Of the 163 ELU types potentially occurring in the park (section 3.1), 83 types (51%) were sampled in the field.

Vegetation communities occurred in as few as one ELU type or across as many as 31 ELU types (Figure 3.4). Average number of ELUs per vegetation community was 8.9. In general, vegetation communities occurred across a variable number of ecological land unit types as expected from community analysis. Communities described from vegetation plot compositional analysis as being generalist (e.g. F5, Central Appalachian Dry-Mesic Chestnut Oak - Northern Red Oak Forest) occurred across numerous ecological land units (n=31), while environmentally restricted communities (e.g. F20, Northern Hardpan Basic Oak - Hickory Forest) occurred across only 3 ecological land units.

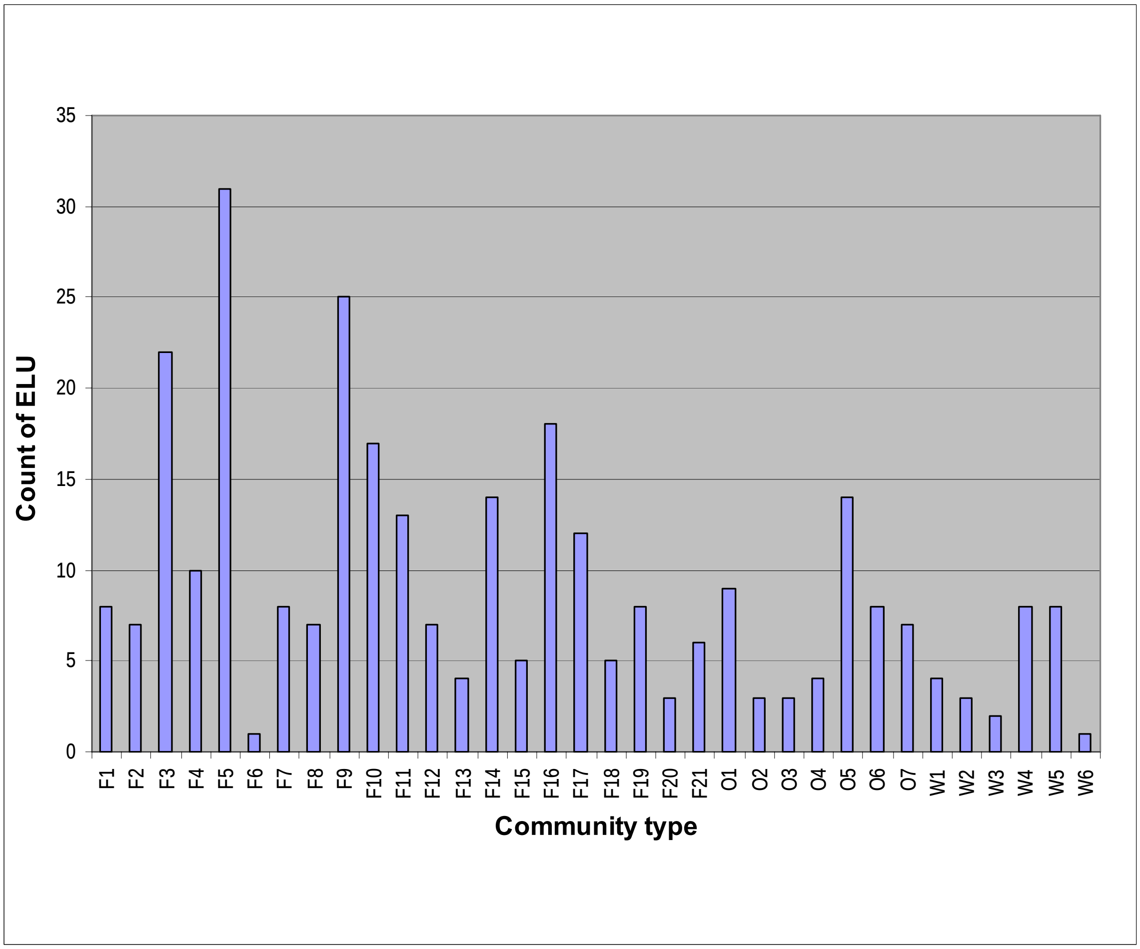

Figure 3.4 Number of ecological land units (ELU) per vegetation community type, from vegetation training data set (n=305).

3.4 Vegetation Map

The output from the CLDA vegetation mapping analysis included vegetation maps for Shenandoah National Park derived from three image sets; the spring AVIRIS image mosaic, the summer AVIRIS image mosaic, and the multitemporal Landsat dataset. In order to create the most accurate final map with complete spatial coverage for Shenandoah National Park, results from these three maps were merged using a rule-based algorithm and the posterior probability maps. Before merging, a cloud mask was developed and applied to the summer AVIRIS image mosaic map to remove areas of bright cloud and dark shadow. Once these areas were excluded, the merging algorithm selected the class at each pixel that had the highest posterior probability from between the two AVIRIS maps. In the case of a tie between the two posterior probabilities, the spring AVIRIS map class was selected, as that image model had a higher overall accuracy and it was acquired prior to a large fire that is evident in the summer image. The less accurate Landsat map was used to fill in small areas at the edge of the park boundary that were not covered by either AVIRIS image mosaic.

The final merged vegetation class map used results from about half of each AVIRIS vegetation map. The final merged image products include: a final vegetation class map (Figures 3.5a, 3.5b, and 3.5c), an image number map that indicates source image for final class assigned (1=spring AV, 2=summer AV, 3=Landsat)(Figure 3.6), and a map showing maximum probability assignments (Figure 3.7). All final map products are in ArcInfo GRID format, 17 m pixel resolution, and projected in Universal Transverse Mercator, Zone 17,North American Datum of 1983 projection.

Figure 3.8 and Table 3.1 list vegetation mapping results by area. Predominant map units by area are *Liriodendron tulipifera-Fraxinus americana-Tilia Americana / Lindera benzoin/Cimicifuga racemosa / Laportea canadensis* “Rich Cove and Slope Forests” (Map code F10), *Quercus montana / Kalmia latifolia / Vaccinium pallidum* (Map code F3), and *Quercus Montana – Quercus rubra / Cornus florida / Viburnum acerifolium* (Map code F5) “Oak/Heath Forests”. Other prominent types are *Tilia americana - Fraxinus americana / Acer pensylvanicum - Ostrya virginiana / Parthenocissus quinquefolia - Impatiens pallida* (Map code F14) “Low Elevation Boulderfield Forests and Woodlands”, *Quercus rubra - Quercus alba - Carya (ovata, ovalis) / Ageratina altissima - Cimicifuga racemosa* (Map code F16) “Montane Oak-Hickory Forests”, and *Fraxinus americana - Carya glabra / Muhlenbergia sobolifera - Helianthus divaricatus - Phacelia dubia* Map code O5) “Mountain/Piedmont Basic Woodlands”.

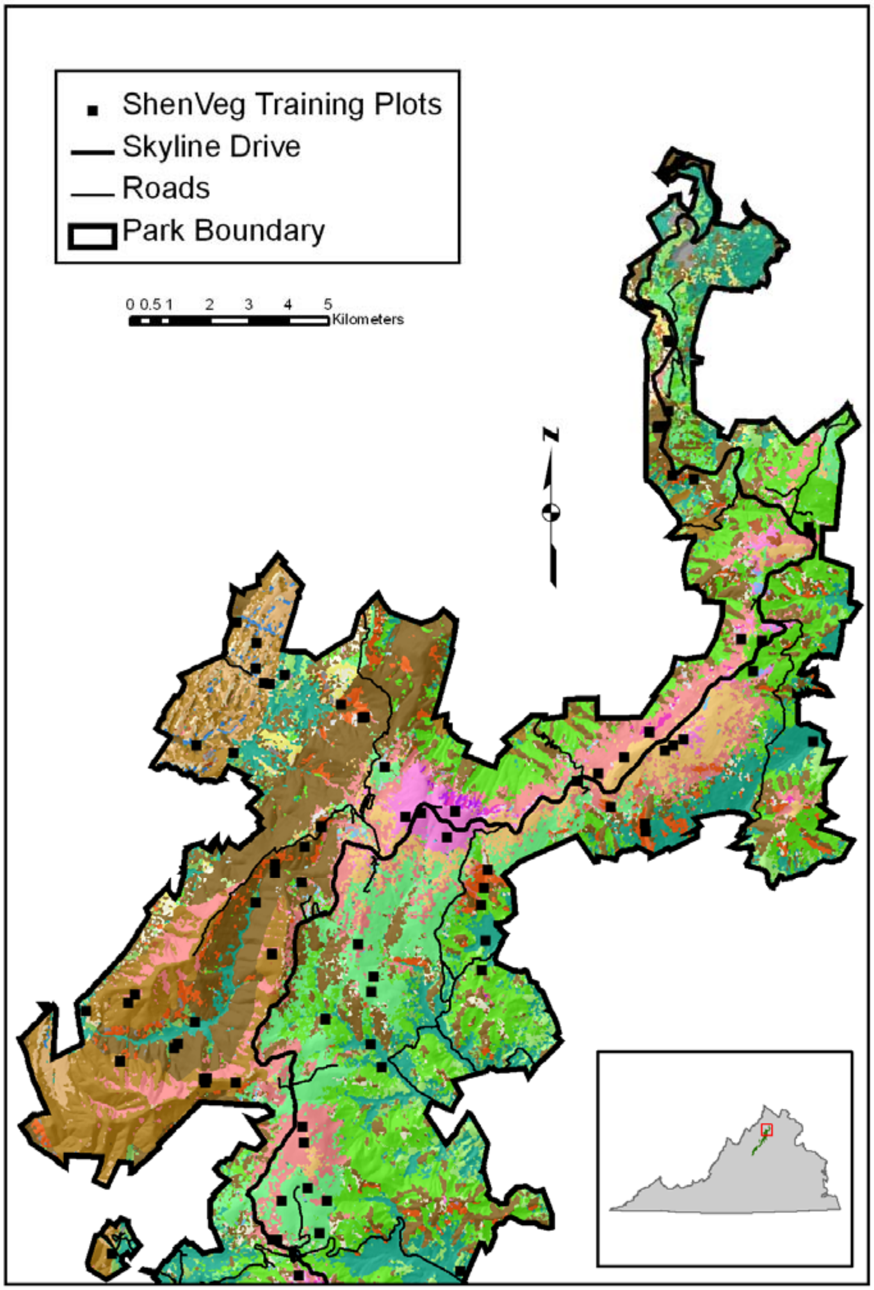

Figure 3.5a Final vegetation map result, version 1.1, North District, Shenandoah National Park, with location of training plots. Refer to figure 3.5d for legend to vegetation community types.

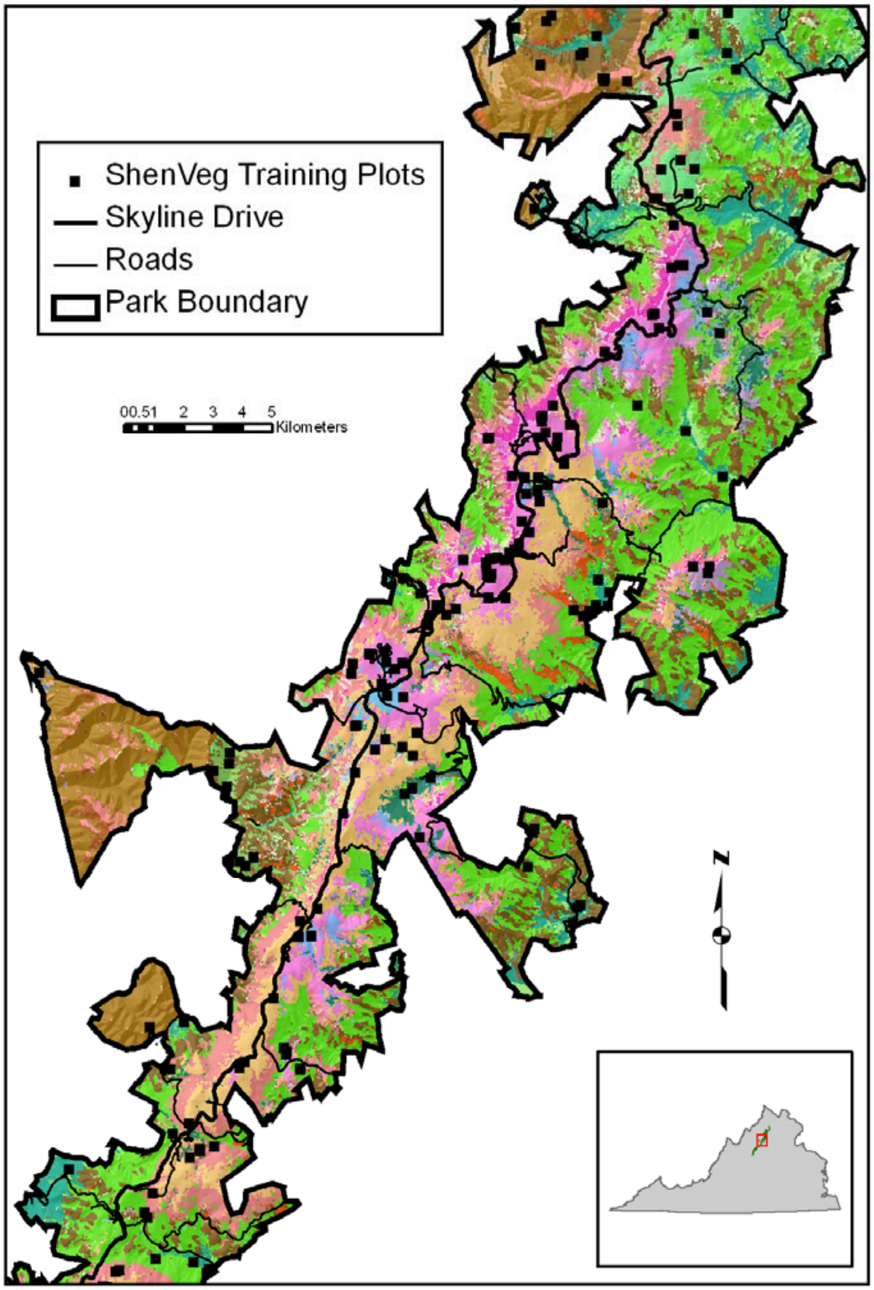

Figure 3.5b Final vegetation map result, version 1.1, Central District, Shenandoah National Park, with location of training plots. Refer to figure 3.5d for legend to vegetation community types.

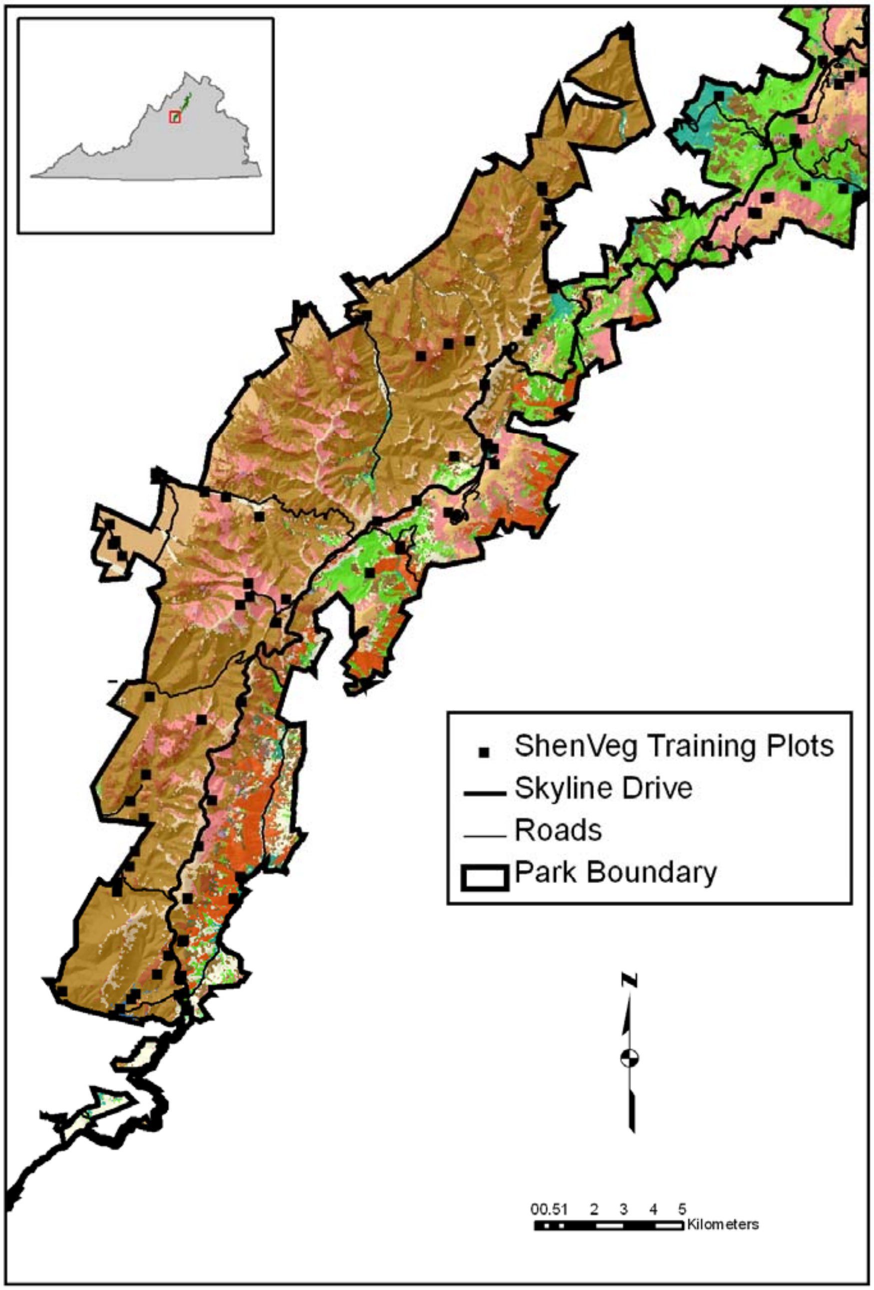

Figure 3.5c Final vegetation map result, version 1.1, South District, Shenandoah National Park, with location of training plots. Refer to figure 3.5d for legend to vegetation community types.

Legend

- F1 - Central Appalachian Pine - Oak / Heath Woodland
- F2 - Chestnut Oak - Black Birch Wooded Talus Slope
- F3 - Central Appalachian / Northern Piedmont Low-Elevation Chestnut Oak Forest
- F4 - Mixed Oak / Heath Forest (Piedmont / Central Appalachian Low-Elevation Type)
- F5 - Central Appalachian Dry-Mesic Chestnut Oak - Northern Red Oak Forest
- F6 - Mid-Atlantic Mesic Mixed Hardwood Forest
- F7 - Central Appalachian Northern Hardwood Forest (Yellow Birch - Northern Red Oak Type)
- F8 - Hemlock - Northern Hardwood Forest
- F9 - Northern Red Oak Forest (Pennsylvania Sedge - Wavy Hairgrass Type)
- F10 - Southern Appalachian Cove Forest (Typic Montane Type)
- F11 - Northern Blue Ridge Montane Alluvial Forest
- F12 - Central Appalachian Acidic Cove Forest (White Pine - Mixed Hardwoods Type)
- F13 - Successional Tuliptree Forest (Circumneutral Type)
- F14 - Central Appalachian Basic Boulderfield Forest (Montane Basswood - White Ash Type)
- F15 - Central Appalachian Rich Cove Forest
- F16 - Central Appalachian Montane Oak - Hickory Forest (Basic Type)
- F17 - Central Appalachian Montane Oak - Hickory Forest (Acidic Type)
- F18 - Central Appalachian Acidic Oak - Hickory Forest
- F19 - Central Appalachian Basic Oak - Hickory Forest (Submontane / Foothills Type)
- F20 - Northern Hardpan Basic Oak - Hickory Forest
- F21 - Black Locust Successional Forest
- O1 - High-Elevation Greenstone Barren
- O2 - High-Elevation Acidic Heath Barren / Pavement
- O3 - High-Elevation Outcrop Barren (Black Chokeberry Igneous / Metamorphic Type)
- O4 - Central Appalachian High-Elevation Boulderfield Forest
- O5 - Central Appalachian Basic Woodland
- O6 - Central Appalachian Circumneutral Barren
- O7 - Central Appalachian Mafic Barren (Ninebark / Pennsylvania Sedge Type)
- W1 - Northern Blue Ridge Mafic Fen
- W2 - Central Appalachian Acidic Seepage Swamp
- W3 - Central Appalachian Woodland Seep
- W4 - Central Appalachian Basic Seepage Swamp
- W5 - High-Elevation Hemlock - Yellow Birch Seepage Swamp
- W6 - Shenandoah Valley Sinkhole Pond (Typic Type)

Figure 3.5d. Map legend for final vegetation map showing vegetation community groups. Refer to pp. 37-48 for community descriptions.

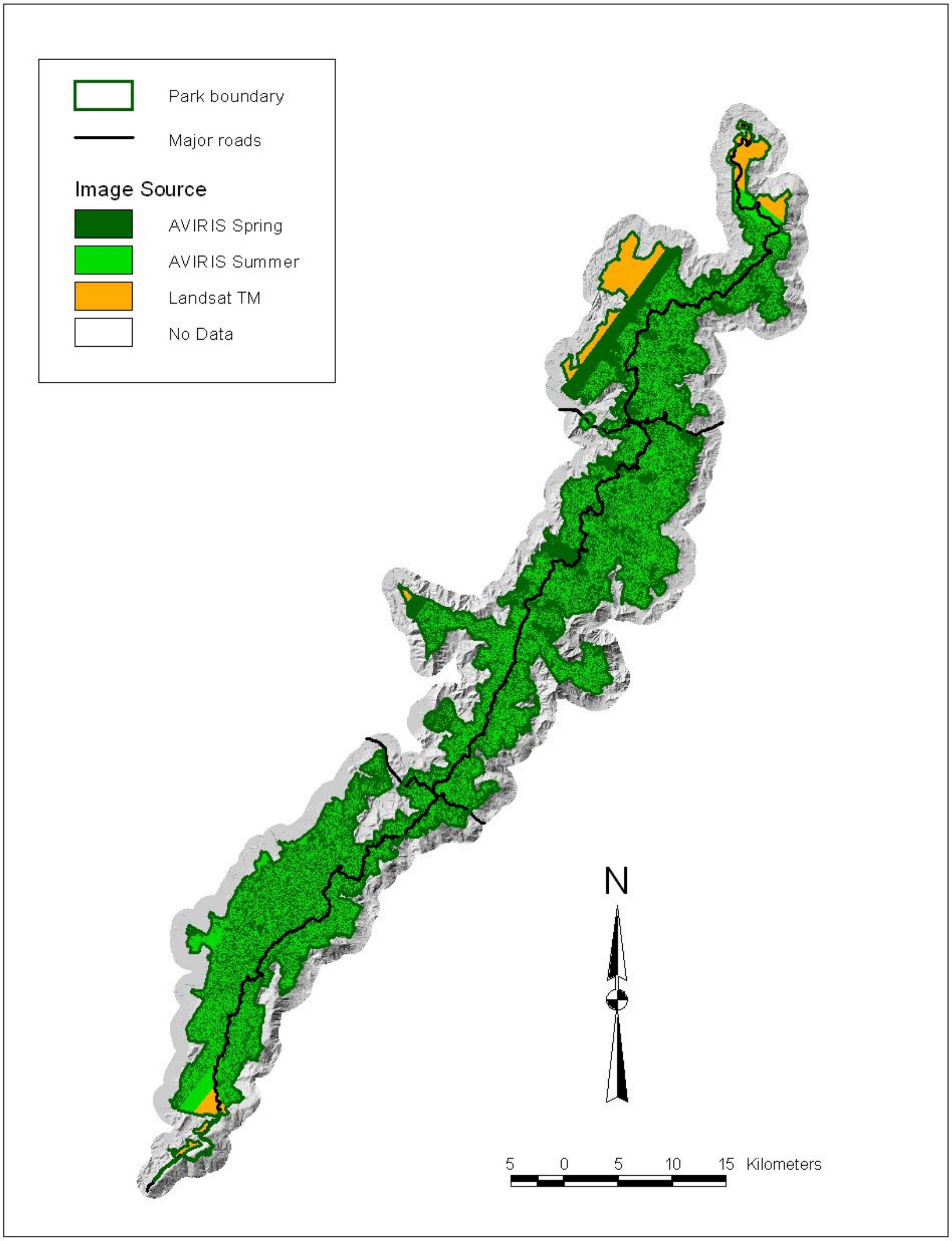

Figure 3.6 Image sources used as inputs to final vegetation mapping result.

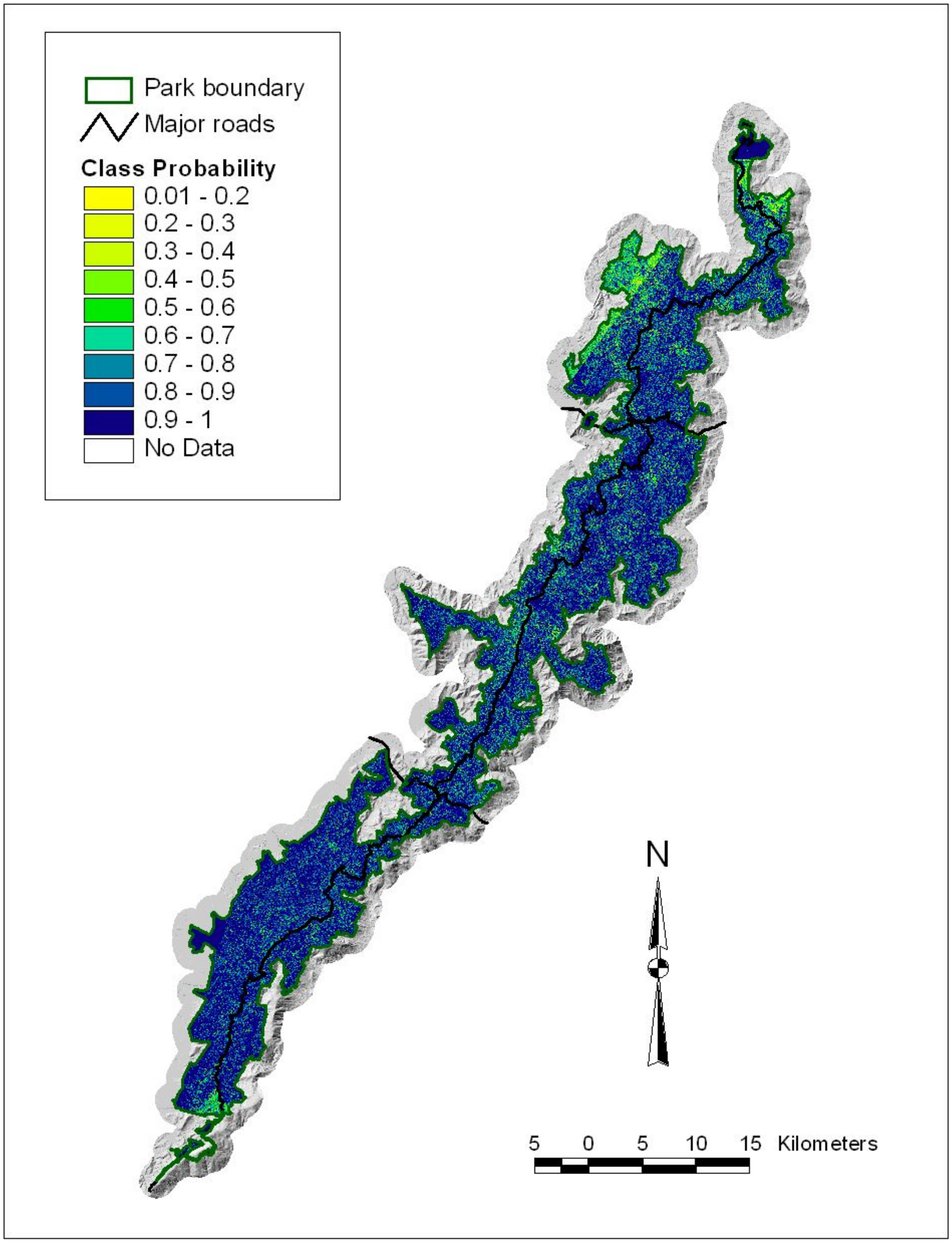

Figure 3.7 Final class probabilities by pixel for vegetation mapping result. Higher probabilities (blue) indicate strong class associations.

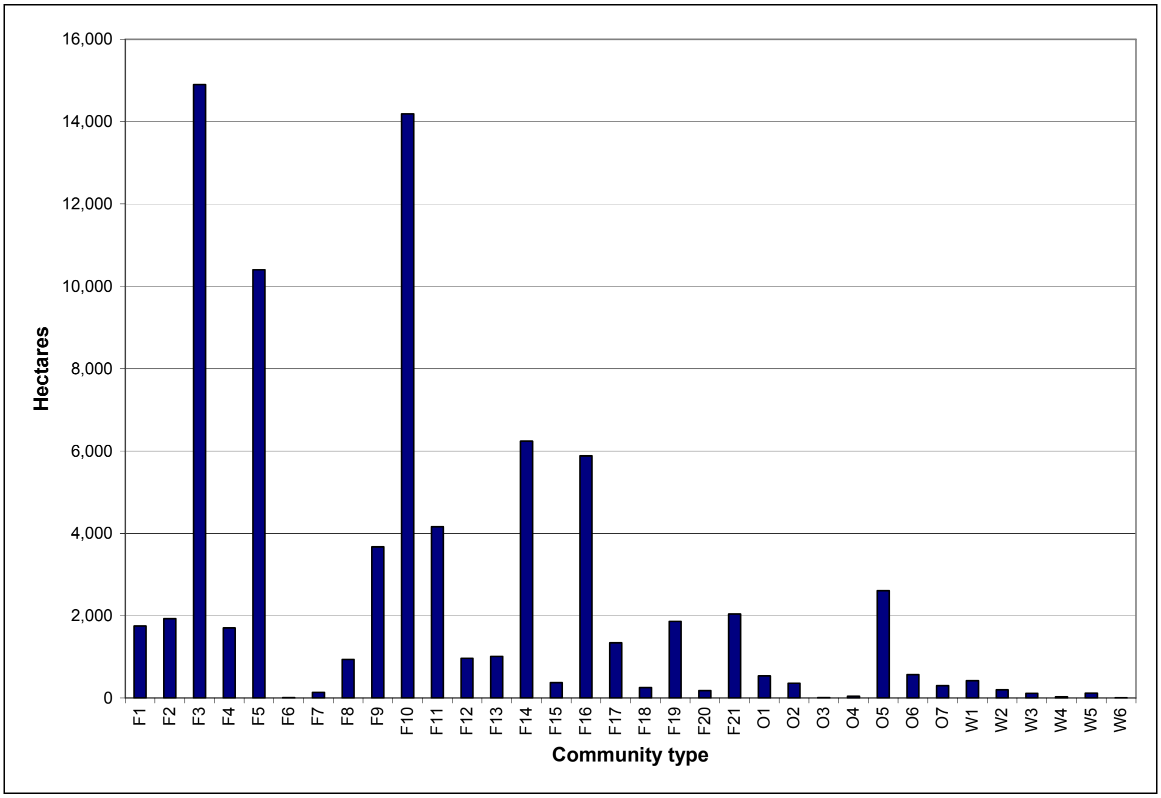

Figure 3.8. Mapped vegetation communities of Shenandoah National Park, by area.

Table 3.1. Mapped vegetation communities of Shenandoah National Park, by area.

Map Code	Common Association Name	Hectares	Percent Area	Cumulative Area
F3	Central Appalachian / Northern Piedmont Low-Elevation Chestnut Oak Forest	14,895	18.80%	18.8%
F10	Southern Appalachian Cove Forest (Typic Montane Type)	14,188	17.90%	36.7%
F5	Central Appalachian Dry-Mesic Chestnut Oak - Northern Red Oak Forest	10,405	13.13%	49.8%
F14	Central Appalachian Basic Boulderfield Forest (Montane Basswood - White Ash Type)	6,237	7.87%	57.7%
F16	Central Appalachian Montane Oak - Hickory Forest (Basic Type)	5,883	7.42%	65.1%
F11	Northern Blue Ridge Montane Alluvial Forest	4,162	5.25%	70.4%
F9	Northern Red Oak Forest (Pennsylvania Sedge - Wavy Hairgrass Type)	3,671	4.63%	75.0%
O5	Central Appalachian Basic Woodland	2,608	3.29%	78.3%
F21	Black Locust Successional Forest	2,039	2.57%	80.9%
F2	Chestnut Oak - Black Birch Wooded Talus Slope	1,925	2.43%	83.3%
F19	Central Appalachian Basic Oak - Hickory Forest (Submontane / Foothills Type)	1,862	2.35%	85.7%
F1	Central Appalachian Pine - Oak / Heath Woodland	1,749	2.21%	87.9%
F4	Mixed Oak / Heath Forest (Piedmont / Central Appalachian Low-Elevation Type)	1,700	2.15%	90.0%
F17	Central Appalachian Montane Oak - Hickory Forest (Acidic Type)	1,342	1.69%	91.7%
F13	Successional Tuliptree Forest (Circumneutral Type)	1,008	1.27%	93.0%
F12	Central Appalachian Acidic Cove Forest (White Pine - Mixed Hardwoods Type)	968	1.22%	94.2%
F8	Hemlock - Northern Hardwood Forest	935	1.18%	95.4%
O5	Central Appalachian Basic Woodland	567	0.72%	96.1%
O1	High-Elevation Greenstone Barren	541	0.68%	96.8%
O7	Central Appalachian Mafic Barren (Ninebark / Pennsylvania Sedge Type)	420	0.53%	97.3%
F15	Central Appalachian Rich Cove Forest	370	0.47%	97.8%
O2	High-Elevation Acidic Heath Barren / Pavement	359	0.45%	98.2%
O6	Central Appalachian Circumneutral Barren	300	0.38%	98.6%
F18	Central Appalachian Acidic Oak - Hickory Forest	256	0.32%	98.9%
W1	Northern Blue Ridge Mafic Fen	201	0.25%	99.2%
F20	Northern Hardpan Basic Oak - Hickory Forest	182	0.23%	99.4%
F7	Central Appalachian Northern Hardwood Forest (Yellow Birch - Northern Red Oak Type)	139	0.18%	99.6%
W4	Central Appalachian Basic Seepage Swamp	117	0.15%	99.7%
W2	Central Appalachian Acidic Seepage Swamp	113	0.14%	99.9%
O4	Central Appalachian High-Elevation Boulderfield Forest	43	0.05%	99.9%
W3	Central Appalachian Woodland Seep	29	0.04%	100.0%
F6	Mid-Atlantic Mesic Mixed Hardwood Forest	12	0.02%	100.0%
O3	High-Elevation Outcrop Barren (Black Chokeberry Igneous / Metamorphic Type)	11	0.01%	100.0%
W6	Shenandoah Valley Sinkhole Pond (Typic Type)	5	0.01%	100.0%

3.5 Accuracy Assessment

3.5.1 Internal Accuracy Assessment:

The trio of CLDA vegetation mapping models from the AVIRIS and Landsat data produced variable success at predicting the assigned vegetation class of the training set. Spring AVIRIS predicted the correct vegetation type out of 33 classes for 83% (88% percent plots correct, or PPC) of 1060 spectral samples. Summer AVIRIS predicted the correct vegetation association out of 32 classes for 82% (87% PPC) of the 932 training sample cases. Multitemporal Landsat TM predicted the correct vegetation type 57% of the time (64% PPC) from 1196 samples. Overall accuracies for the two AVIRIS maps are remarkably similar and surpass the desired 80% threshold, though different classes are best predicted on different maps. The Landsat model accuracy around 60% is similar to accuracy achieved for Landsat data in the literature for such specific and detailed vegetation classes. Landsat is probably less powerful at discriminating detailed vegetation classes because it has fewer, broader spectral bands than the AVIRIS hyperspectral imagery and its pixel size of 30m is less compatible with the field sampling protocol used in this study than the 17m AVIRIS image pixel size.

The accuracy of the final merged map for Shenandoah National Park was assessed internally by sampling the final map with the training sample locations and computing the percent plots correct (PPC) for each class and the entire map (Appendix 6, Table A.6.1). The overall PPC accuracy of the merged map was **88%**. This accuracy was higher than the overall accuracies of the individual image models because only the best predicted areas from each map were incorporated into the final merged product. Five of the association level classes were mapped with a training set PPC lower than 80% accuracy.

3.5.2 Field validated accuracy assessment:

Once all the possible map classes were recorded from the final map, all possible map classes were compared to the first (presumably most likely) recorded field class for each validation site. We tabulated results for accuracy assessment separately for 2004 and 2005 field surveys since the protocols and field crews varied between campaigns. We also report results from a "paper" accuracy assessment analysis using other vegetation field plots collected for long-term ecological monitoring (LTEM) and plant protection activities. The results of this analysis are shown in Appendix 6. Overall field validation accuracy for the 2004 accuracy assessment campaign was **64%** (Appendix 6, Table A.6.2). By-class accuracy ranged from a high of 100% to a low of 0%. However, the number of validation plots in some classes was low. Overall field validation accuracy from the 2005 accuracy assessment campaign was **51%** (Appendix 6, Table A.6.3), again reflecting low sample sizes. By-class accuracy ranged from a high of 100% to a low of 0%. Overall accuracy reported from a "paper" accuracy assessment using previously collected plot data was **51%** (Appendix 6, Table A.6.4). Once again, by-class accuracy ranged from a high of 100% to a low of 0%.

While overall field validated accuracy appears low, a tabulation of accuracy by area using the 2004 accuracy assessment campaign data reveals that 80% of the park by area is mapped at an 80% accuracy level, and 95% of the park by area is mapped at 64% accuracy level (Table 3.2).

Table 3.2 Cumulative accuracy by cumulative park area. Vegetation associations mapped in Shenandoah National Park in this effort are arranged in descending order by park area. Accuracy figures are from 2004 field accuracy assessment.

Map Code	Common Association Name	Hectares	Cumulative Area	Accuracy 2004 AA	Cumulative Accuracy
F3	Central Appalachian / Northern Piedmont Low-Elevation Chestnut Oak Forest	14,895	18.8%	83.0%	
F10	Southern Appalachian Cove Forest (Typic Montane Type)	14,188	36.7%	89.0%	
F5	Central Appalachian Dry-Mesic Chestnut Oak - Northern Red Oak Forest	10,405	49.8%	70.0%	
F14	Central Appalachian Basic Boulderfield Forest (Montane Basswood - White Ash Type)	6,237	57.7%	60.0%	
F16	Central Appalachian Montane Oak - Hickory Forest (Basic Type)	5,883	65.1%	82.0%	
F11	Northern Blue Ridge Montane Alluvial Forest	4,162	70.4%	100.0%	
F9	Northern Red Oak Forest (Pennsylvania Sedge - Wavy Hairgrass Type)	3,671	**75.0%**	100.0%	**83.4%**
O5	Central Appalachian Basic Woodland	2,608	78.3%		
F21	Black Locust Successional Forest	2,039	**80.9%**	56.0%	**80.0%**
F2	Chestnut Oak - Black Birch Wooded Talus Slope	1,925	83.3%	0.0%	
F19	Central Appalachian Basic Oak - Hickory Forest (Submontane / Foothills Type)	1,862	**85.7%**	55.0%	**69.5%**
F1	Central Appalachian Pine - Oak / Heath Woodland	1,749	87.9%	68.0%	
F4	Mixed Oak / Heath Forest (Piedmont / Central Appalachian Low-Elevation Type)	1,700	**90.0%**	50.0%	**67.8%**
F17	Central Appalachian Montane Oak - Hickory Forest (Acidic Type)	1,342	91.7%	60.0%	
F13	Successional Tuliptree Forest (Circumneutral Type)	1,008	93.0%	32.0%	
F12	Central Appalachian Acidic Cove Forest (White Pine - Mixed Hardwoods Type)	968	94.2%	14.0%	
F8	Hemlock - Northern Hardwood Forest	935	**95.4%**	100.0%	**63.7%**
W5	Central Appalachian Basic Woodland	567	96.1%		
O1	High-Elevation Greenstone Barren	541	96.8%		
O7	Central Appalachian Mafic Barren (Ninebark / Pennsylvania Sedge Type)	420	97.3%		
F15	Central Appalachian Rich Cove Forest	370	97.8%	50.0%	
O2	High-Elevation Acidic Heath Barren / Pavement	359	98.2%		
O6	Central Appalachian Circumneutral Barren	300	98.6%		
F18	Central Appalachian Acidic Oak - Hickory Forest	256	98.9%	100.0%	
W1	Northern Blue Ridge Mafic Fen	201	99.2%		
F20	Northern Hardpan Basic Oak - Hickory Forest	182	99.4%		
F7	Central Appalachian Northern Hardwood Forest (Yellow Birch - Northern Red Oak Type)	139	99.6%	40.0%	
W4	Central Appalachian Basic Seepage Swamp	117	99.7%	0.0%	
W2	Central Appalachian Acidic Seepage Swamp	113	99.9%		
O4	Central Appalachian High-Elevation Boulderfield Forest	43	99.9%		
W3	Central Appalachian Woodland Seep	29	100.0%		
F6	Mid-Atlantic Mesic Mixed Hardwood Forest	12	100.0%		
O3	High-Elevation Outcrop Barren (Black Chokeberry Igneous / Metamorphic Type)	11	100.0%		
W6	Shenandoah Valley Sinkhole Pond (Typic Type)	5	100.0%		

4. Discussion/Conclusion

The results of this project demonstrate innovative application of the latest techniques in vegetation mapping using hyperspectral imaging and landscape modeling. Mapping results are generally consistent with previous mapping efforts (by area) and show that the USNVC can be reliably mapped with techniques other than manual interpretation of aerial photography. In fact, by exploiting the fine spectral specificity of hyperspectral imaging and the spatial heterogeneity of environmental gradient models, much more information can potentially be extracted on growing environments than can be visually interpreted. The fact that Association-level classes can be mapped using these techniques is an important finding.

However, the modeling techniques listed here do have limitations, and the field accuracy assessment demonstrates that these approaches may not always be amenable to the same type of error assessment as when using traditional aerial photography and polygon-based photo interpretation. For example, the internal accuracy assessment of the vegetation models agrees extremely well with the field data classified into vegetation communities. In other words the model fits the training data. However, the field validation results do not fit nearly as well to the model results. This discrepancy can be interpreted in several ways. One possibility is that the training data are biased towards natural communities, and these are over represented in the resulting models at the cost of accurately representing the amount of disturbed or successional forests in the park. For instance, class F21 was sampled somewhat rarely in the original vegetation sampling (i.e. we did not sample a lot of disturbed Ash-Black Locust forest), but this class turned out to be much more common in the validation sample. The map reflects the original field data, so this class is probably underrepresented, and is obviously a lot more common than the original field sample would suggest.

A second possibility is that the accuracy assessment field data do not accurately account for the intergraded nature of the forest communities, and may miss the “correct” community type in a nearby pixel. Although we attempted to account for this in the accuracy assessment evaluation by looking at the vegetation class of the majority of pixels in a neighborhood around the sampled pixel, the fact that multiple possible vegetation community types were recorded for many of the field plots made this difficult to properly address. In addition, the sample size of the accuracy assessment field set is small relative to the size of the park and the number of classes mapped. The distribution of accuracy assessment points was also based on a draft map using an earlier and less accurate set of assumptions on vegetation community distribution. Therefore, some classes were under-sampled in the final accuracy assessment, and some classes were not sampled at all.

Potential solutions to the low accuracy reported for some classes are to collapse classes into higher levels of the USNVC hierarchy, add additional accuracy assessment sample points, or to revise mapping methodologies. First, collapsing classes from association into alliance or higher level categories has appeal in that classes of similar floristic composition can be combined to minimize commission errors (e.g. incorrect assignment of classes when compared to ground truth). However, the classification scheme derived for SHEN (Appendix 2) defines 34 associations, 31 alliances, and 14 formations. Collapsing classes to the alliance level does not result in significant reduction in specificity between classes, and collapsing classes to the formation level may be so general that valuable information is lost. Clearly some intermediate level of reclassification is warranted.

Secondly, it would be possible to increase statistical confidence in accuracy assessment by increasing the number of samples for each class. Guidelines for the USGS-NPS vegetation mapping program call for a minimum of 30 samples per class (Mike Story, NPS, pers. comm.). For the 34 vegetation communities mapped in Shenandoah NP, this would mean sampling 1020 plots for accuracy assessment. While a noble goal, we found plot sampling to the detail required to assess association-level communities in this park to be exceedingly difficult. Two years of effort at field accuracy assessment yielded only 292 sampled plots. Logistical difficulties in navigating to plots often resulted in sampling only 1-2 plots per day, and additional time was required at the plots for the field crews to key vegetation into their closest association. Additional samples could be gleaned from air-photo interpretation, but confidently interpreting associations from aerial images is very difficult. This problem needs additional investigation for a satisfactory result in heavily vegetated (and heavily disturbed) mixed-deciduous forest dominated park units of the eastern U.S.

Lastly, mapping methods could be revised to re-assess and re-combine individual class probability maps for better class representation. Some communities classified from plot vegetation sampling are small patch types or are exceedingly rare in the park. While we attempted to map all classes present in the training data set (i.e. all types classified from vegetation plot sampling), some types may need to be eliminated as too small to map. For these classes, notations can be made of their presence in the surrounding matrix forest community. Additionally, it may be possible to restrict distributions of over-mapped communities by manipulating maps of predicted class probability using ecological land unit maps and knowledge of vegetation occurrence. For example, alluvial forest communities should not occur on upper hill slopes, and therefore it may be appropriate to minimize probabilities for this class using GIS operations within hill slope ecological land unit types.

Environmental gradient models helped to place the vegetation communities in context of the physical environment, although not always with the desired specificity. Figure 4.1 illustrates that a number of community types occur across a broad range of ecological land unit types. This result may mean that certain communities (e.g. the Oak/Heath types F5 and F3) are generalists, or that the models are not incorporating the fine scale information on micro climate or soil properties necessary to distinguish the habitat preferences of certain communities. However, environmental gradient models (incorporated as topographic variables) were selected as significant discriminating variables in the CLDA models in both the AVIRIS and Landsat-based classifications. The information content of the image bands clearly overwhelmed the topographic variables in relative importance in the AVIRIS-based models (Figure 2.3), but the topographic variables added significant information to the Landsat-based multi-temporal models (Figure 2.4).

The greatest benefit of this approach, however, is the nature of the processing itself. Since the models are quantitative and digital, the input parameters can be reset and reprocessed, allowing for fine tuning of the output products. This ability to quickly tweak and re-run the models will allow for future revision of the map products to meet the needs of the park and national map accuracy standards, or to incorporate new variables in the modeling process. It is our hope that the results of this project will be revised and updated as new information becomes available, or as issues with the initial mapping are discovered. We attempted to create a flexible, objective, and repeatable digital process so that changes in vegetation cover can be represented in map form for improved management of the park. While many issues remain unresolved regarding accurately mapping vegetation associations from imagery, we hope that our project has taken a positive step toward incorporating new methods and image sources into these efforts.

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